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UNIVERSAL BRIDGE B221
AND
LOW IMPEDANCE ADAPTOR Q221

INSTRUCTION MANUAL

WAYNE KERR

UNIVERSAL BRIDGE B221

AND

LOW IMPEDANCE ADAPTOR Q221

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WAYNE KERR UNIVERSAL BRIDGE B221
RANGE
OFF
MAINS
110/230V 40/60~
SENSITIVITY
TRIM
G
TRIM
C

Part 1 - Universal Bridge B221

INTRODUCTION

The design of the Universal Bridge is based on the transformer ratio-arm principle. A full explanation of the theory of operation is given in Wayne Kerr Monograph No. 1, 'The Transformer Ratio-Arm Bridge', available on request.

Balance of the Unknown impedance is against Standards of conductance and capacitance in parallel. Tappings on the two Bridge transformers, connected to decade controls, permit measurements to be made accurately on a wide range of impedance in any quadrant of the complex plane.

An internal oscillator adjusted to 1592c/s ($\omega = 10^4$) provides the Source voltage. A buffer amplifier isolates the oscillator from the Bridge circuits, to which four-terminal connexions can be made. The Detector is a tuned two-stage amplifier, incorporating a sensitivity control, with a double-shadow 'magic eye' associated with each stage. Instruments can be supplied to special order with Source and Detector tuned to 1000c/s.

Components can be measured *in situ*. Network characteristics, values of transfer admittance and the effectiveness of transformer screens can be determined. The effect of stray capacitance in assemblies such as test jigs can be eliminated.

The Low Impedance Adaptor, described fully in the second part of this Handbook, extends the range of measurement to include lower values of resistance and inductance and very high values of capacitance.

A modification to standard (1592c/s) or special (1000c/s) Bridges enables the instruments to be used with an external source and detector for measurements at frequencies within the band 50c/s to 20kc/s. Full information on such operation, including that of the Low Impedance Adaptor, is given in an Appendix.

SPECIFICATION

Mains Input	100–125 volts, 200–250 volts, 40–60c/s. Power consumption approximately 25 watts.	
Source Frequency	1592c/s ±1 per cent ($\omega = 10^4$) (1000c/s to special order).	
Conductance Ranges	1 0—0·111 μ*Mho*	(∞—9*M*Ω)
	2 0—1·11 μ*Mho*	(∞—0·9*M*Ω)
	3 0—11·1 μ*Mho*	(∞—90*k*Ω)
	4 0—111 μ*Mho*	(∞—9*k*Ω)
	5 0—1111 μ*Mho*	(∞—900Ω)
	6 0—11·1 *mMho*	(∞—90Ω)
	7 0—111 *mMho*	(∞—9Ω)

Discrimination 0·02 per cent of maximum.

Accuracy ±0·2 per cent* from 111*mMho* (9Ω) to 0·01 μ*Mho* (100*M*Ω).

On Ranges 6 and 7, correction must be made for the leads.

Conductive term can be positive or negative.

---

* Better than 0·1 per cent if Standards are checked.

Capacitance and	1	0—11·1 $\mu\mu F$	$(\infty$—900$H)$
Inductance Ranges	2	0—111 $\mu\mu F$	$(\infty$—90$H)$
$(L=-1/\omega^2 C, \omega^2=10^8)$	3	0—1111 $\mu\mu F$	$(\infty$—9$H)$
	4	0—0·0111μF	$(\infty$—0·9$H)$
	5	0—0·111 μF	$(\infty$—90$mH)$
	6	0—1·11 μF	$(\infty$—9$mH)$
	7	0—11.1 μF	$(\infty$—0·9$mH)$

Range 1 covers 0—1·11$\mu\mu F$ $(\infty$—9000$H)$, and other ranges correspondingly altered, with C multiplier in 0·1 position.
Discrimination 0·02 per cent of maximum.
Capacitance accuracy $\pm$0·25 per cent* from 11·1μF to 0·1$\mu\mu F$.
Measurements to 0·0002$\mu\mu F$ with reduced accuracy.
Inductance accuracy $\pm$0·25 per cent if oscillator frequency is measured; otherwise better than $\pm$2 per cent.
Capacitive term can be positive or negative.

Dimensions	Width	17in. (43 cm.)
	Height	11½in (29cm.)
	Depth	7½in. (19cm.)
Weight	25lb. (11kg.)	

The extension of the measurement range obtained with the Adaptor is specified in Part 2.

PRINCIPLE OF OPERATION

The operation is summarized in the Introduction, to which reference should be made, and a simplified diagram of the circuit arrangement is shown in Fig. 1, where Z_u and Z_s are the Unknown and Standard impedances respectively.

Balance will be indicated by the Detector, connected to the secondary of the current transformer $T2$, when equal currents flow from either end of the centre-tapped primary of $T2$. In this condition, the potential across the primary will be zero and, therefore, the right-hand terminals of Z_u and Z_s will be at Neutral potential. Thus the same voltage is applied to both impedances and, for equal currents to flow in the two halves of $T2$ primary, the resistive and reactive components of the Unknown impedance must be equal to those of the Standard.

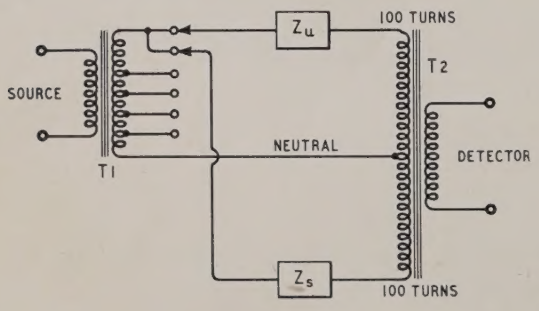


Fig. 1. Principle of Operation

For a given value of Unknown impedance the Bridge can be balanced in three ways. The value of the Standards can be adjusted, differing potentials can be applied to the two impedances, or the currents they pass can be fed through unequal numbers of turns on the primary of $T2$. A selection of taps on $T2$ primary and on the secondary of the voltage transformer $T1$ permit a wide range of Unknown values to be measured against a minimum number of Standard components.

The Standard components are resistive and capacitive but, by reversing the sense of their connexions to the current transformer, an imped-

* Better than 0·1 per cent if Standards are checked.

ance in any quadrant of the complex plane can be measured. As the Standards are connected in parallel, the Bridge measures the equivalent parallel components of the Unknown.

Since, at balance, no potential exists across $T2$ primary, it is possible to connect an impedance between the right-hand terminal of Z_u and Neutral without affecting the accuracy of measurement. The only effect will be to reduce the sensitivity of the Detector and this can be compensated for by increasing the gain.

It is possible also to connect an impedance between the left-hand terminal of Z_u and Neutral. This shunt impedance will reduce the voltage applied to Z_u, but will reduce also the voltage applied to Z_s, in proportion to the turns ratio. The accuracy is therefore unaffected and any loss in sensitivity can again be compensated for by increasing the detector gain.

The transformers are so designed that very heavy shunting is possible without seriously affecting the accuracy of measurement. Components can in most instances, therefore, be measured *in situ*.

CIRCUIT DESCRIPTION

POWER SUPPLY

The Instrument operates from supplies of 40 to 60 c/s, consuming about 25 watts. A circuit diagram is provided at the back of this Handbook and from this it can be seen that the primary of the mains transformer is wound in two sections. These are connected in series for 200–250V operation and in parallel for 100–125V. The full-wave rectifier, V4, supplies approximately 15mA at 250 V.

SOURCE

Refer to Fig. 2. One section of the double triode operates in an LC oscillator circuit and a fraction of the alternating potential is fed at low impedance to the right-hand section of $V1$, serving as a buffer amplifier. Inductor $L2$ has a ferrite pot core and the frequency of oscillation is set to precisely 1592c/s by adjustment of the trimmer capacitor $C6$. A potential of approximately 30V is developed across $T1$ secondary.

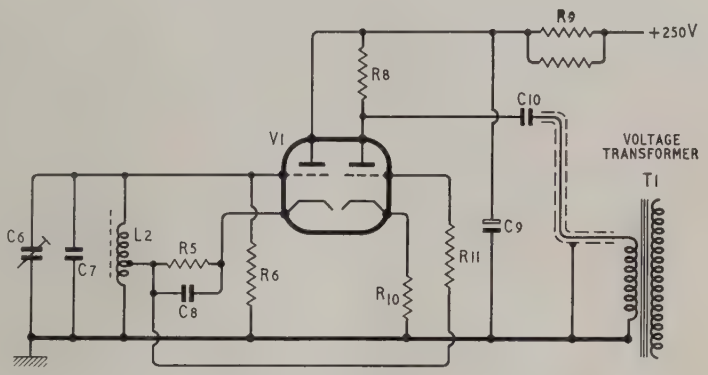


Fig. 2. Source Circuit

DETECTOR

The Detector circuit, shown in Fig. 3, consists of a two-stage tuned-anode amplifier using ferrite pot cores and silvered-mica capacitors. A double-shadow 'magic eye' is connected to each stage, providing four degrees of sensitivity overall. The Sensitivity control ($RV4$) affects both 'magic eyes' and balance is indicated by maximum shadow.

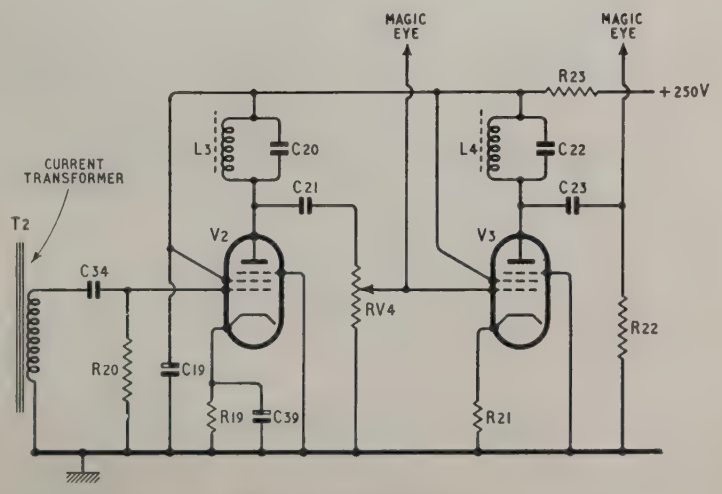


Fig. 3. Detector Circuit

BRIDGE CIRCUIT

The Bridge circuit, shown in simplified form in Fig. 4, consists essentially of the voltage transformer *T*1, tapped to provide an accurately-related selection of voltages across the Unknown and Standard impedances, and the current transformer *T*2.

The primary of *T*2 consists of two separate windings on a core of high-permeability metal. One winding is fed from the Unknown impedance and the other from the Standards circuit. Balance occurs when the ampere-turns in the two windings are of equal magnitude but opposite sense.

The Neutral connexion from the voltage transformer is taken to the centre-tap of the Standards winding on the current transformer. By connecting the Standards to a winding of appropriate sense, positive or negative conductance and capacitance can be measured.

The Neutral connexion of the Unknown winding on the current transformer is linked to that of the Standards winding for most two- and three-terminal measurements. The link is removed for four-terminal measurements, to provide two Neutrals.

STANDARDS

For details of the Standards arrangement the complete circuit diagram at the back of this Handbook should be referred to.

Switched decades are provided by two fixed resistors (*R*15, *R*16) and two fixed capacitors (*C*12, *C*14) which can be switched independently in 1-turn steps to taps of from 0 to 10 turns on the voltage transformer. This gives each Standard effectively ten different values.

To provide the continuously-variable conductance decade, a linear potentiometer (*RV*2) is connected across nine turns of the voltage transformer and produces a variable voltage across a close-tolerance resistor (*R*17). This is illustrated in Fig. 5. The continuously-variable reactive decade is provided by a variable air-spaced capacitor (*C*11) connected to the 3-turn tap on *T*1.

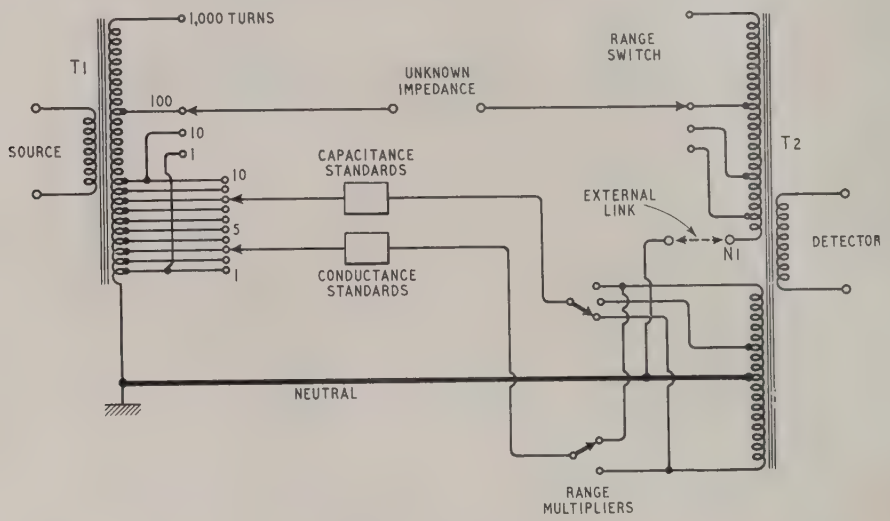


Fig. 4. Bridge Circuit

The values of the conductance and capacitance Standards are so chosen that they normally cover

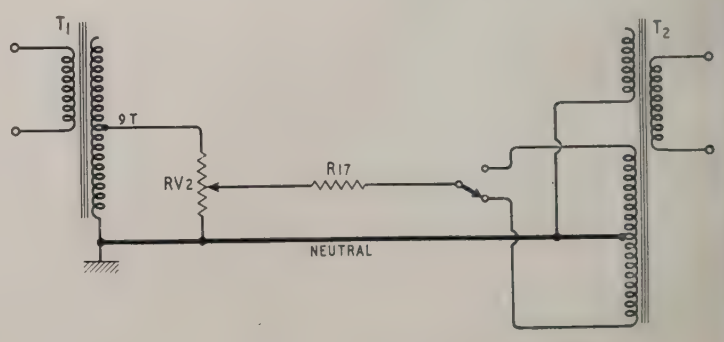


Fig. 5. Third *G* Decade

the same range. However, to extend the effective range of one Standard with respect to the other, $T2$ is tapped to provide a capacitance range one-tenth of normal. The range multiplier switches have the following settings:

G 1 and —1. (—1 for negative conductance).

C 0·1, 1 and —1. (—1 for inductance).

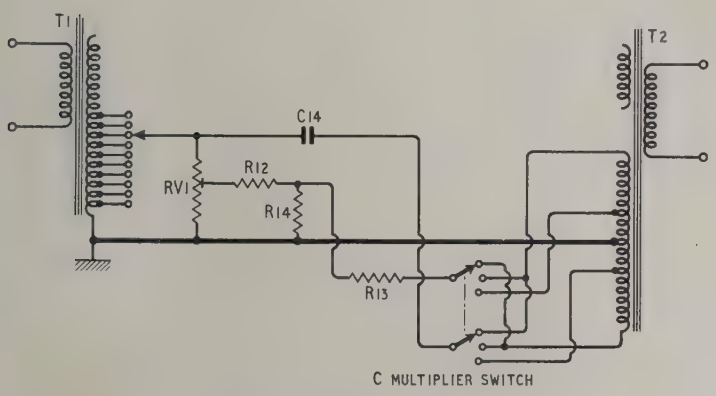


Fig. 6. *C* Phase Trimming

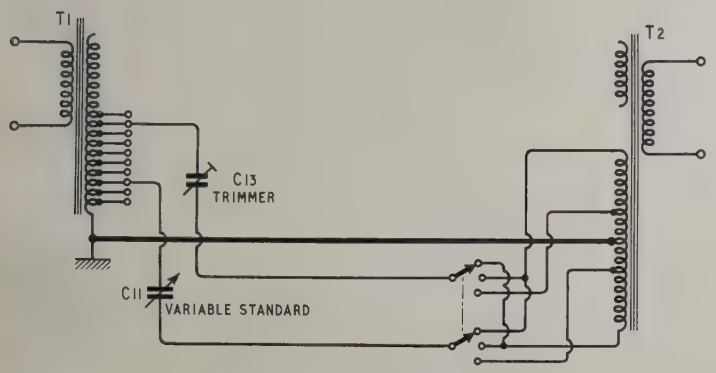


Fig. 7. Residual Capacitance

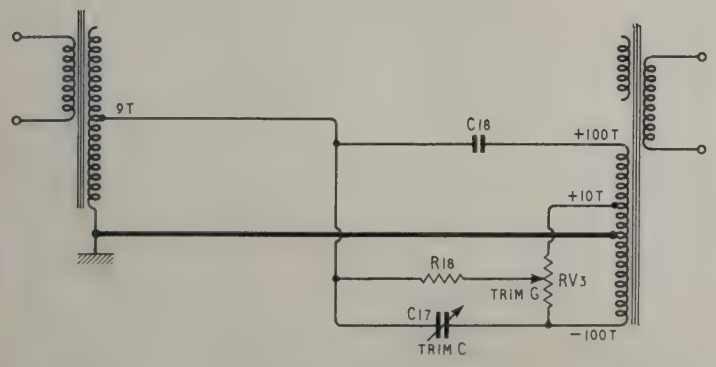


Fig. 8. Trim Controls

TRIMMING OF STANDARDS

The two main resistive Standards ($R15$, $R16$) are wire-wound and slightly inductive. Their phase angle is reduced to zero by means of trimming capacitors ($C36$, $C15$ and $C16$) connected in parallel with them.

The 0·001μF Standard ($C12$) does not require correction. Losses in the 0·01μF Standard ($C14$) are compensated for by a resistive current fed into the current transformer through a tap of opposite sense. This is shown in Fig. 6. $RV1$ is adjusted to balance out the resistive current produced by the losses in $C14$. $R12$, $R13$ and $R14$ form an attenuator to obviate the use of high-value resistors which might become unstable. $R13$ is always connected to a tap having the same number of turns as that connected to $C14$ but of opposite sense. The trimming holds, therefore, for all positions of the *C* multiplier switch.

RESIDUAL CAPACITANCE TRIMMING

To compensate for the residual capacity of the continuously-variable Standard $C11$, a trimmer ($C13$) feeds a current into $T2$ through a tap of opposite sense. The arrangement is shown in Fig. 7. Whatever the connexion of $C11$ to the current transformer, the trimmer $C13$ is always connected to a tap having the same number of turns but of opposite sense. Once $C13$ is adjusted, therefore, the trimming holds for any position of the *C* multiplier switch.

MAIN BRIDGE TRIMMING

The circuit arrangement of the two external trimming controls (Trim *G*, Trim *C*) is shown in Fig. 8.

A compensating voltage from the 9-turn tap on $T1$ is fed via $R18$ to the slider of a potentiometer (Trim *G*) connected across the +10 and —100 taps of $T2$. This allows the effective value of $R18$ to be made either positive or negative.

The capacitive trimming consist

of a fixed 33μμF capacitor (*C*18) and a 100μμF variable capacitor (*C*17) connected across the positive and negative ends of the Standards winding on the current transformer. The same voltage as that used for conductance trimming is fed to their junction. With this arrangement the effective value of *C*17 can be made either positive or negative.

UNKNOWN CONNEXIONS AND RANGE SWITCH

The circuit arrangement of the connexions to the Unknown impedance and the facilities for range changing are shown in Fig. 9.

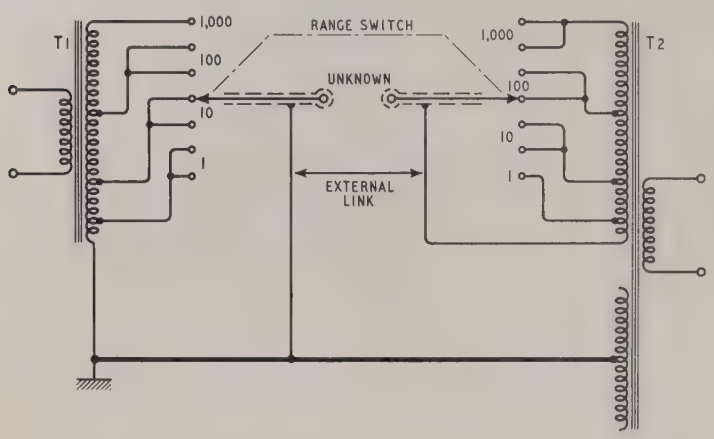


Fig. 9. Range Switch

The impedance to be measured is connected between the voltage transformer and the Unknown winding of the current transformer via the Range switch (*S*7). The Range switch connexions to the taps on the transformers are such that in each of the seven positions the preceding range is effectively multiplied by ten.

Physical connexion to the Unknown is by means of two external coaxial cables. The screen of each cable is connected to the associated Neutral of the Bridge. For two- and three-terminal measurements the two Neutrals are linked: this method of connexion prevents the inherent capacitance of the cables shunting the measurement terminals.

MEASUREMENT VOLTAGE

The a.c. voltage applied to the component being measured on the Bridge cannot be specified accurately, measurements being made by comparative values of the Standard and Unknown currents. The voltage varies from range to range but is constant over any one range. Approximate values are:

Bridge Range	R.M.S. Voltage
1	30 V
2 and 3	3 V
4 and 5	0·3 V
6 and 7	30mV

OPERATING INSTRUCTIONS

MAINS CONNEXIONS

The Bridge is adjusted for 200- to 250-volt operation before leaving the factory. To adjust for 100- to 125-volt operation the instrument must be removed from its case. To do this, first turn the Range switch to position 1, all decade switches to 5, and then remove the four bright hexagon bolts from the corners of the front framework. The alternative wiring to the mains transformer is illustrated in Fig. 10.

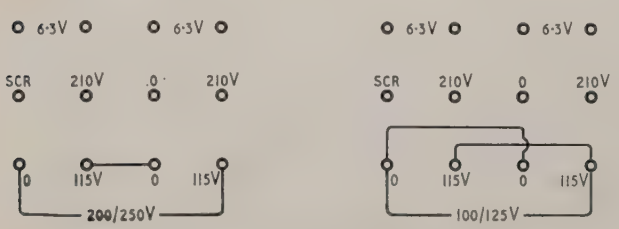


Fig. 10. Mains Transformer Tags

The mains lead should be wired to a three-pin plug as follows:

GREEN to Earth,

BLACK or BLUE to Neutral,

RED to Line.

Warning: If the Bridge is to be connected to equipment which is already earthed, the procedure described under 'In Situ Measurements' must be applied before the Bridge is connected to the mains supply.

The Bridge is switched on by means of the toggle switch on the left-hand side of the front panel. After a few seconds the two 'magic eyes' should glow.

MEASUREMENT LEADS

The Bridge is supplied with two coaxial cables with sockets at each end, two short leads with a coaxial plug at one end and a crocodile clip at the other, two short leads with crocodile clips and moulded Neutral clips, a moulded shorting bar and a low-capacitance connector.

When the two coaxial leads have been connected to the E and I plugs on the Bridge, the moulded shorting bar can be clipped into position (at the Bridge end of the leads). This operation links the two Neutral circuits of the Bridge and must be carried out before any initial zero balance adjustments are made. The shorting bar must remain in position for all two- and three-terminal measurements.

When making three-terminal measurements, one of the moulded Neutral clips is attached to either of the cable sockets at the end remote from the instrument. The crocodile clip fitted to these assemblies is for connexion to the third terminal of the circuit under test. The two main connexions are made using the clip leads fitted with coaxial plugs.

When it is required to use the two Bridge Neutrals independently for four-terminal measurements, the shorting bar must be removed. A Neutral clip should then be attached to the end of each coaxial cable.

Due to the high gain of the Detector circuit, the Bridge is susceptible to pick-up through the measurement lead (*I*) connected to the Detector. To reduce this pick-up to a minimum it is advisable to keep the Bridge clear of any strong electromagnetic fields.

INITIAL ZERO BALANCE

1 Connect the two coaxial cables to the E and I plugs of the Bridge and clip the shorting bar into position.

2 Remove any connexions from the remote end of the cables (except the clip leads) and set all Bridge switches and dials to zero.

3 Turn the Sensitivity control fully clockwise, the *G* and *C* switches to 1 and the Range switch to position 7; the Range number appears in an aperture between the two 'magic eyes'.

4 Adjust the Trim *G* and Trim *C* controls for maximum shadow on the 'magic eyes'.

Once adjusted, this zero balance will remain satisfactory for all normal measurements but, for extreme accuracy, it should be checked frequently. For maximum accuracy on the lowest capacitance range the initial zero balance procedure should be repeated with the Range switch in position 1 and the measurement leads disposed as they will be when the Unknown is connected.

The Bridge is now ready for use but, if for any reason the trimming controls are disturbed, the Bridge *must* be re-trimmed.

TEST JIGS

It is possible, within the limits of the trimming controls, to balance out the conductance and stray capacitance of test jigs, etc. An accurate absolute measurement of the component under test can therefore be made. With the test jig alone connected to the measurement leads the Trim controls should be adjusted as described in steps 3 and 4 of the previous section. This trimming will be correct only on the range for which the adjustment was made. If the component is now connected to the jig, its correct value can be measured directly.

CONDUCTANCE MEASUREMENTS

1 Carry out the Initial Zero Balance procedure, return the Sensitivity control to mid-position and connect the Unknown to the coaxial leads by means of the crocodile clip adaptors.

2a If the order of conductance is known, turn the Range switch to the appropriate position and, if the Unknown is slightly inductive, change the setting of the *C* multiplier switch from 1 to —1. Balance the Bridge by adjusting the *G* decade controls, rotating the Sensitivity control clockwise as balance is approached and, if necessary, adjusting the variable *C* decade control.

2b If the order of conductance is not known, rotate the Range switch until the eyes *just begin* to close and then proceed as in 2a. When the order of conductance is thus established it may indicate that a further change of range will provide increased reading accuracy.

Note: *If on Range 7 the eyes are fully closed, reduce the sensitivity and balance on this range.*

When conductances greater than 10 millimhos are measured (resistances of less than 100 ohms), the resistance of the measurement leads and connectors must be taken into account. This is described on page 19.

RESISTANCE MEASUREMENTS

Resistance is measured as conductance and derived by taking the reciprocal. A table of reciprocals is provided at the back of this Handbook. When resistances of less than 100 ohms are

measured, a correction for the measurement leads must be made. This is described on page 19.

CAPACITANCE MEASUREMENTS

1 Carry out the Initial Zero Balance procedure, return the Sensitivity control to mid-position and connect the Unknown to the coaxial leads by means of the crocodile clip adaptors.

2a If the order of capacitance is known, turn the Range switch to the appropriate position and balance the Bridge by adjusting the *C* decade controls. As balance is approached, increase the sensitivity and, if necessary, adjust the variable *G* decade control.

2b If the order of capacitance is not known, rotate the Range switch until the eyes *just begin* to close and then proceed as in 2a. When the order of capacitance is thus established it may indicate that a further change of range will provide increased reading accuracy.

Note: *If on Range 7 the eyes are fully closed, reduce the sensitivity and balance on this range.*

When measuring capacitances of less than 1000μμF, it is advisable to replace the crocodile clip adaptor connected to the *I* lead with the low-capacitance connector supplied. The *C* multiplier switch should be set to the 0·1 position only when an adequate reading cannot be obtained in the normal (1) position. When set to 0·1 the reading obtained from the Bridge must be *divided by ten.*

Ceramic Capacitors

With certain capacitors the value changes considerably with the value of d.c. polarizing voltage. In such instances a polarizing potential can be applied as shown in Fig. 11. The blocking capacitor should have a value at least 100 times that of the Unknown.

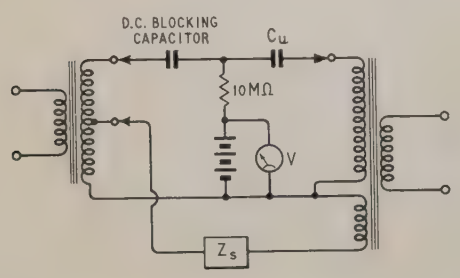


Fig. 11. Polarizing Ceramic Capacitors

Electrolytic Capacitors

The alternating potential applied across capacitors being measured on the Bridge is so low that it is generally unnecessary to polarize them. If it is necessary to measure them with a d.c. potential applied, the arrangement shown in Fig. 12 can be

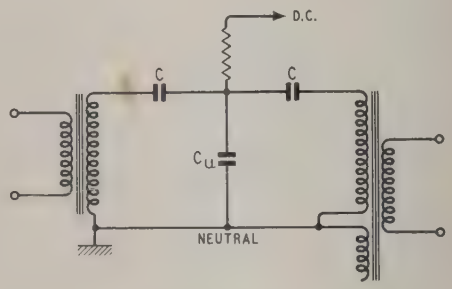


Fig. 12. Polarizing Electrolytic Capacitors

used. The two capacitors, *C*, should be reasonably matched and of known value, very much smaller than C_u. The Unknown capacitance is given by

$$C_u = C^2/C_m$$

where C_m is the value measured on the Bridge. The phase-shift introduced by this circuit may necessitate setting the *G* multiplier switch to —1 when balancing out the losses.

Loss Angle

The loss angle or power factor of capacitors can be computed from the values measured on the Bridge.

$$\tan \delta = G/\omega C \qquad \simeq$$

$$\cos \varphi = G/Y \simeq G/\omega C = \tan \delta$$

G in μMhos. C in μF

An allowance for the impedance of the measuring leads must be made when dealing with large-value capacitors. This is described on page 19.

INDUCTANCE MEASUREMENTS

Inductance is measured as an equivalent negative capacitance and exactly the same procedure is adopted as for capacitance measurements but with the C multiplier switch in the —1 position. To convert the capacitance reading to inductance, a simple calculation is necessary using the equation

$$L = 10^6/[(2\pi f)^2 C]$$

where *L* is the inductance in Henrys, *C* the Bridge

reading in microfarads and f the Bridge frequency in cycles per second.

Since for the Bridge frequency of 1592c/s the term $2\pi f = 10\,000$, the calculation is simplified to one of taking the reciprocal of C and repositioning the decimal point. Under these conditions the accuracy of measurement is ± 2 per cent. For extreme accuracy the oscillator frequency should be measured and the inductance calculated from the above equation. A table of reciprocals is provided at the back of this Handbook.

The reciprocal of the conductance term indicated on the Bridge is the *parallel* resistance of the inductor. The equivalent *series* components of inductance and resistance can be derived using the expressions given on page 24. The value of inductance is approximately the same for series and parallel circuits only with high-Q coils.

When Range 6 or 7 is used for the measurement of small-value inductors, a correction must be made to allow for the inductance of the measurement leads and the leakage inductance of the Bridge transformers. This is described on page 19.

Iron-cored Inductors

Great care must be taken when interpreting the results obtained from measurements on iron-cored coils and transformer windings. With mains transformers, for example, the core will have only its initial permeability due to the low value of the a.c. potential applied from the Bridge. The effective permeability at full operating voltage may be as much as twenty times higher.

With high-permeability materials such as mu-metal, the effective permeability changes so rapidly with excitation, even at very low levels of magnetization, that widely different values of inductance may be obtained on different ranges of the Bridge or even on two Bridges of the same pattern. Therefore, unless the operating conditions are simulated, the measurements made are of value only for comparison purposes.

Inductors Passing D.C.

It is often necessary to measure inductors carrying a known value of direct current and three ways of doing this are shown in Fig. 13. In Fig. 13(a) the d.c. supply, with a large-value capacitor by-passing it, is connected in series with the inductor being measured. This arrangement cannot be used, however, if one terminal of the d.c. supply is connected to Earth, as this would short-circuit the Bridge voltage transformer. The maximum values of current that may be passed through the Bridge are given in

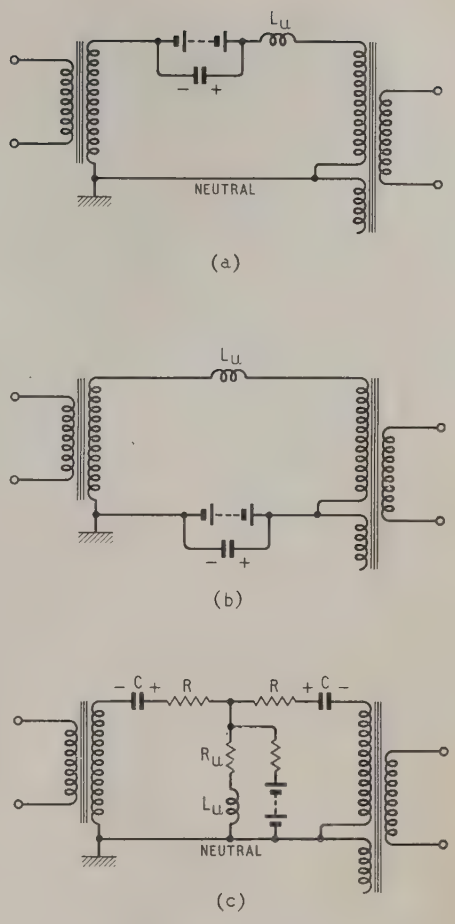


Fig. 13. Inductors Passing D.C.

Table 1. Under no circumstances must these values be exceeded.

With the arrangement shown in Fig.13(b) the moulded Neutral link is not used and the by-passed d.c. supply is connected between the two Neutral leads. If one terminal of the d.c. supply is earthed it must be connected to the Neutral of the E lead. The limitations on current specified in Table 1 must be observed.

If the reactance of the by-pass capacitor shown in Fig. 13(a) and (b) is significant, it can be allowed for by calculating its equivalent inductance value at the Bridge frequency and *adding* this to the effective *series* value derived from the measurement.

TABLE 1

MAXIMUM PERMISSIBLE CURRENT THROUGH BRIDGE

Range	1	2	3	4	5	6	7
Max. D.C.	50mA	50mA	0·5A	0·5A	1·0A	1·0A	1·0A

Where it is required to pass a current through the inductor in excess of the values given in Table 1, the arrangement shown in Fig. 13(c) may be used. The resistors R must have a value of 50 to 100 times the impedance of the Unknown, and the capacitors C a reactance which is low compared with the value of R. The T-network may then be regarded as equivalent to a capacitor in parallel with a resistor connected straight across the Bridge. The equivalent *series* components of the Unknown are given by:

Series Resistance, $R_u = R^2.G_m$

Series Inductance, $L_u = R^2.C_m$

where G_m and C_m are the values measured on the Bridge.

COMPLEX IMPEDANCE MEASUREMENTS

The range of impedance covered by the Bridge can be measured in any quadrant of the complex plane, the result being expressed as positive or negative conductance in parallel with capacitance or inductance. If it is desired to express this as a series combination, the necessary conversion must be calculated using the expressions given on page 24.

The measurement procedure is the same as that for conductance or capacitance but the G and C multiplier switches must be set to the appropriate positions for the nature of the Unknown.

ERRORS IN THE MINOR COMPONENT

The dominant component in a *parallel* combination of resistance and reactance is that with the lower ohmic value. The term 'minor' refers, therefore, to the component with the higher ohmic value and, where this exceeds ten times the value of the major component, the accuracy in measuring the minor component is reduced. An accuracy of $\pm 0{\cdot}25$ per cent in measuring the major component will be obtained provided that all three decade controls are in use.

SCREENED COMPONENTS

When resistors or capacitors are enclosed in metal cases and one terminal of the component is connected to the case, this terminal should be connected to the E lead from the Bridge. This method of connexion ensures minimum stray pick-up by the case and the component can then be measured in the usual manner.

When measuring sub-standard three-terminal capacitors, care must be taken to ensure that the conditions of measurement are the same as those under which the capacitor was calibrated. A three-terminal capacitor is shown schematically in Fig. 14. In addition to the main capacitance

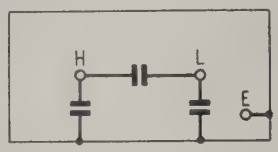


Fig. 14. Three-terminal Capacitor

between the high- and low-potential terminals (H and L) there is the stray capacitance between each terminal and the metal case, E. Calibration is normally carried out with the low-potential side joined to the case. Under these conditions the stray capacitance between the L terminal and the case is shorted out, leaving the capacitance between H and the case in parallel with the main capacitance between H and L.

If the sub-standard is connected to the Bridge with the case connected to Neutral, *both* stray capacitances in the sub-standard will be neutralized and the reading obtained will be low. To this reading must be added the capacitance between H and the case. This can be measured on the Bridge by connecting the case to the voltage (E) lead from the Bridge, the H terminal to the current (I) lead and the L terminal to Neutral.

TEMPERATURE COEFFICIENT MEASUREMENTS

Since leads of any length may be used without their capacitance affecting the accuracy of the reactance measurement, and as lead resistance can be allowed for (see page 19), the Bridge is ideally suited to the measurement of temperature and other coefficients of components placed in an oven, refrigerator, pressure chamber, humidity chamber, etc. If full use is made of the decade controls, the discrimination of balance is 0·01 per cent of maximum for the range in use.

IN SITU MEASUREMENTS

It is often convenient to be able to measure an impedance *in situ*, without disconnecting any other components which may be associated with it. Moreover, with certain test jigs, it is often impossible to 'disconnect' the effective shunt and stray capacitances. Generally speaking, any circuit can be resolved into a three-terminal network, the arrangement being as shown in Fig. 15.

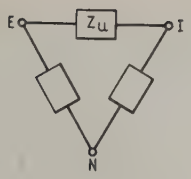


Fig. 15. Three-terminal Network

The impedance to be measured is Z_u and the effect of impedances E–N and I–N must be removed. The arrangement can be considered as a π-network and is shown in Fig. 16 in this form, connected to the Bridge. Z_{EN} shunts the voltage transformer and Z_{IN} shunts the current transformer. In many instances these shunting effects may be disregarded (for reasons given under 'Principle of Operation'). In Fig. 17, for example, it may be possible to measure the impedance between A and B without disconnecting the other components simply by connecting point C to the Bridge Neutral.

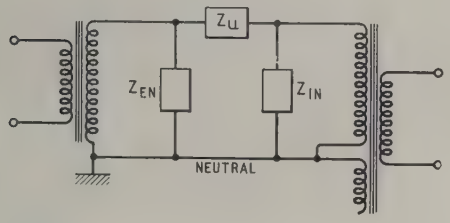


Fig. 16. Three-terminal Measurements

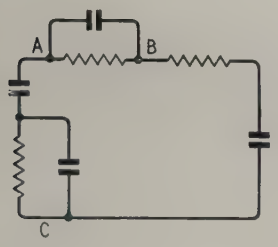


Fig. 17. In Situ Measurements

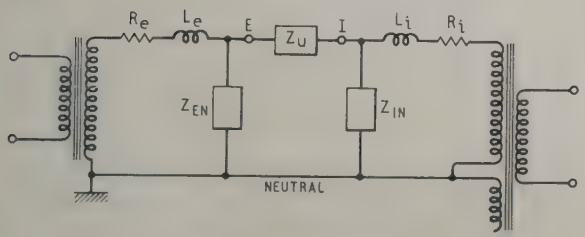


Fig. 18. Shunting Effect

Important: *Under no circumstances must the inner of either measurement lead be connected to Earth while the green wire of the Bridge mains cable is earthed.*

The Neutral circuit of the Bridge is earthed internally and such action would short-circuit both Bridge transformers.

When it is necessary to connect either measurement lead (inner of E or I) to the chassis or framework of the equipment under test, this equipment must first be isolated from Earth. If this is not practicable, the Bridge must be isolated from Earth by disconnecting the green wire of the mains cable from the Earth pin of the plug. Care must be exercised while operating the Bridge in this condition and the Earth connexion should be replaced when isolation is no longer necessary.

When the shunting effects (Z_{EN} and Z_{IN} of Fig. 16) cannot be ignored, the series resistance and leakage inductance of the Bridge transformers must be taken into account. The measurement circuit must now be drawn as in Fig. 18 and a simple calculation, described in succeeding paragraphs, must be made in order to correct the readings obtained from the Bridge.

The loading effect of the Unknown impedance itself is small and can be ignored. It is only when the shunt impedances are low compared with Z_u that errors arising are of importance. Therefore Z_u can be considered as an open-circuit and the shunting effects on either side of the Unknown can be considered separately.

The fall in potential at E caused by the load Z_{EN} will depend on the ratio of Z_{EN} to the impedance of R_e and L_e, the effective series resistance and leakage inductance of the voltage transformer. A similar argument applies to the current side of the Bridge and the two effects are additive.

Table 2 gives the average values of effective resistance and leakage inductance of the windings for each tapping. When it is necessary to correct for shunt loading the following formulae may be used to calculate the true value of impedance, Z_u, from the value read on the Bridge, Z_m.

With loading on the voltage transformer only:

$$Z_u=(1-Z_e/Z_{EN}).Z_m$$

where $Z_e=R_e+j\omega L_e$ ($\omega=10^4$).

With loading on the current transformer only:

$$Z_u=(1-Z_i/Z_{IN}).Z_m$$

where $Z_i=R_i+j\omega L_i$.

With both transformers loaded:

$$Z_u=[1-(Z_e/Z_{EN}+Z_i/Z_{IN})].Z_m.$$

TABLE 2

Turns (Tap)	Voltage Transformer (T1)			Current Transformer (T2)		
	R_e	L_e	X_e	R_i	L_i	X_i
1	0·025Ω	0·36μH	0·0036Ω	0·017Ω	0·63μH	0·0063Ω
10	0·025Ω	0·36μH	0·0036Ω	0·032Ω	0·9μH	0·009Ω
100	1·2Ω	18·0μH	0·18Ω	1·54Ω	46·0μH	0·46Ω
1000	72·0Ω	1·44mH	14·4Ω	68·0Ω	1·02mH	10·2Ω

If the loading is at the end of leads, add 75·6 milliohms and 0·3μH per yard of Uniradio 32. The transformer taps in use for the various ranges are given in Table 3.

TABLE 3

RANGE	TRANSFORMER TURNS	
	Voltage (T1)	Current (T2)
1	1000	1000
2	100	1000
3	100	100
4	10	100
5	10	10
6	1	10
7	1	1

NETWORK CHARACTERISTICS

The facility for three-terminal measurements and the readiness with which either or both the conductance and reactance Standards can be made effectively negative merely by switching to a winding of reverse sense, make the Bridge a most efficient instrument for measuring the characteristics of networks. Transfer admittance, for example, is measured simply by the arrangement

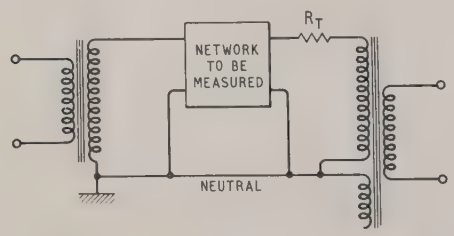


Fig. 19. Network Characteristics

shown in Fig. 19. The input of the network is connected between the voltage terminal and Neutral. The output is connected, in series with its terminating resistance R_T, between the *I* lead and Neutral. The right-hand side of R_T will be at Neutral potential when the Bridge is balanced and the network will then be correctly terminated.

Let the transfer admittance, defined as the current flowing in the terminating resistor for unit input voltage, be $|Y|\angle\theta$. Then, at balance:

$$|Y|\angle\theta = \pm G_m \pm j\omega C_m$$

where G_m and C_m are the values of conductance and capacitance read on the Bridge.

Then $\quad |Y| = (G_m^2 + \omega^2 C_m^2)^{\frac{1}{2}}$

and $\quad \theta = tan^{-1}(\pm \omega C_m / G_m)$.

ATTENUATOR MEASUREMENTS

The characteristics of attenuators can be measured quite simply on the Bridge and the circuit arrangement is shown in Fig. 20. With the resistor R_T in the position shown the attenuator is correctly terminated at balance, when the right-hand side of R_T will be at Neutral potential.

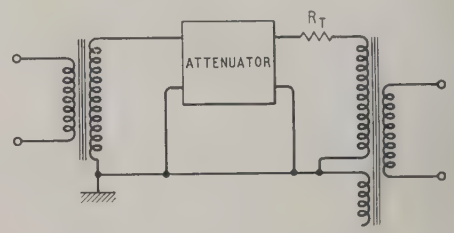


Fig. 20. Attenuator Measurements

If the Bridge is balanced with the attenuator set to zero, a value equal to the matching impedance R_T will be measured. If the attenuator steps are now switched in, the voltage attenuation can be calculated accurately from the ratio of the apparent change in value of R_T.

EFFECTIVENESS OF TRANSFORMER SCREENS

The effectiveness of screens between transformer windings can be determined using the arrangements shown in Fig. 21. The method of measurement when the transformer has a single inter-winding screen is shown in Fig. 21 (a) and, in Fig. 21(b), the method of connexion when each winding has a separate screen is shown.

With perfect screening there should be no feed through the transformers if connected as shown. Any effective capacitance between the windings will be indicated on the Bridge.

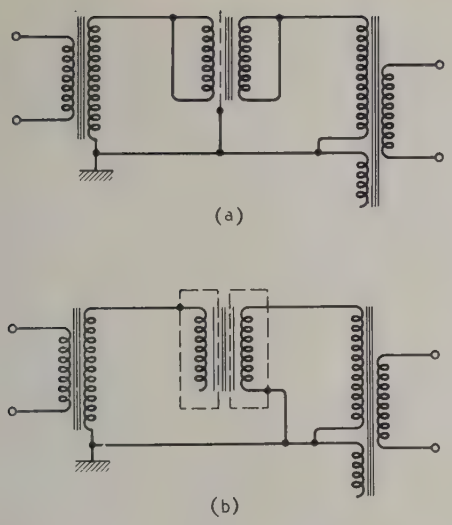


Fig. 21. Transformer Screens

LEAD CORRECTIONS

Lead Resistance

The total series resistance of the two 2-ft measurement leads is of the order of 0·1 ohm. For the highest accuracy, however, the resistance can be measured with the Bridge as follows:

1 Set the Range switch to position 6 or 7 (whichever is used to measure the Unknown).

2 With the measurement leads open-circuit but disposed as they were when the Unknown was connected, balance the Bridge (with all decade controls at 0) by means of the two Trim controls.

3 Connect a carbon resistor of near value to the resistance of the Unknown and measure its apparent conductance. Convert this reading to resistance ($R=1/G$ when resistance alone is measured).

4 Remove the measurement leads from the Bridge and connect the short crocodile-clip leads, with the resistor still attached, direct to the *E* and *I* plugs.

5 Measure the new value of conductance and convert the reading to resistance.

6 The resistance of the leads is obtained by subtracting the value obtained in step 5 from that obtained in step 3.

The series resistance of the Bridge transformers must be added to the lead resistance. Details of the transformers, for the various ranges, are given in Tables 2 and 3 (page 18).

Lead Inductance

The total series inductance of the two 2-ft measurement leads can be taken as 0·4 microhenry. To this value must be added the leakage inductance of the Bridge transformers. This is given in Tables 2 and 3 (page 18).

Corrected Measurement

When an impedance of less than 100 ohms has been measured and it is desired to correct for the leads and Bridge transformers, the result must first be converted from the *parallel* to the equivalent *series* components. These series components are corrected more easily if expressed as resistance and reactance.

Let the Bridge readings be G and $+C$ or $-C$.

Then parallel components of resistance (R_p) and reactance (X_p) are given by:

$$R_p=1/G \qquad \text{and} \qquad X_p=1/2\pi fC$$

Equivalent *series* components are given by:

$$R_s=R_p/(1+Q^2) \qquad \text{and} \quad X_s=\pm X_p/(1+1/Q^2)$$

where $Q=R_p/X_p$.

The corrected series values are obtained by subtracting the total resistance (leads + transformers) from R_s, and by subtracting the reactance of the total inductance (leads + transformer leakage) from X_s, [i.e. corrected series reactance $=X_s-2\pi f$ (inductance of leads + leakage inductance of Bridge transformers)]. Denoting these true series values by R_{ST} and X_{ST}, the result can be converted back to the *parallel* components, if desired, by the expressions:

$$\text{True } R_p=R_{ST}\,(1+Q^2) \text{ and}$$

$$\text{True } X_p=X_{ST}\,(1+1/Q^2).$$

When X_s represents inductive reactance, the true value, X_{ST}, will be less than X_s.

When X_s represents capacitive reactance, this must be regarded as negative. The true value in this instance will be more negative by the amount [$2\pi f$ (inductance of leads + leakage inductance of Bridge transformers)].

Important: *No attempt should be made by unskilled personnel to service the Bridge. Maintenance, and particularly any trimming using the pre-set controls, must be carried out by a qualified service engineer in accordance with the following instructions.*

SOURCE AND DETECTOR

The location of any fault in the oscillator or detector amplifier circuits will be indicated by checking the valve potentials against the values shown in Table 4. These readings were obtained with an AVOmeter model 7 (negative lead to chassis) and are average values: variations of up to ±20 per cent must be expected.

TABLE 4

Valve	Electrode	Pin No.	Avo Range	Voltage
V1	Cathode 1	8	100V d.c.	35V
V1	Cathode 2	3	10V d.c.	4·2V
V1	Anode 1	6	400V d.c.	250V
V1	Anode 2	1	400V d.c.	120V
V2	Cathode	2	10V d.c.	1·5V
V3	Cathode	2	10V d.c.	1·1V
V3	Screen	7	400V d.c.	75V
V4	Cathode	7	400V d.c.	255V

OVERALL GAIN

To check the overall gain, first set-up the Bridge according to the Initial Zero Balance procedure (page 13). Leave the Sensitivity control at maximum and adjust the variable conductance control to read 0·2. The most sensitive 'magic eye' section should close completely. This degree of sensitivity is required only when the Low Impedance Adaptor is in use: for all normal Bridge measurements one-tenth of such sensitivity provides adequate discrimination.

OSCILLATOR FREQUENCY

The oscillator frequency is adjusted in the final test procedure to 1592c/s±0·25 per cent. If a Frequency Standard or Frequency Counter is available, it can be fed with the measuring potential from the Bridge. The Source frequency will be obtained with an accuracy determined by the Standard or Counter.

An alternative method, depending only on the Bridge itself and two components, can be used if the Bridge Standards have been checked (see pages 21 and 22). The components required are a high-stability resistor and a high-precision mica capacitor. The exact values are not important but should be about $10k\Omega$ and $0{\cdot}01\mu F$ ($1k\Omega$ and $0{\cdot}1\mu F$ could be used as an alternative). The method is as follows:

1 Measure the resistor and record the value of conductance G.

2 Measure the capacitor and record the value of capacitance C.

3 Connect the two components in series and measure the effective conductance G_m and effective capacitance C_m of the combination.

It can be shown that

$$\omega=\left\{G_m/[(C^2/G)\,(1-G_m/G)]\right\}^{\frac{1}{2}}. \quad . \quad . \quad .(1)$$

or $$\omega=(G/C)\,.\,(C/C_m-1)^{\frac{1}{2}} \quad . \quad . \quad . \quad . \quad . \quad .(2)$$

Equation (1) or (2) can be used to establish accurately the angular frequency of the Bridge Source. The tables used for the calculation should preferably be five-figure. If the Bridge Standards were checked correctly, the values of G, C, G_m and C_m should be obtained with an accuracy of ±0·1 per cent. The angular frequency will then be obtained with an accuracy of better than ±0·3 per cent.

BRIDGE ACCURACY

An important feature of the Universal Bridge is the ease with which the accuracy can be checked and, if necessary, the Standards re-set. As described earlier, the B221 uses only one, fixed, Standard per decade; the steps of the decades, and the Bridge ratios, being obtained from the ratio-transformers. The Standards fitted to the Bridge have an accuracy of 0·1 per cent and should have a long-term stability of the same order. The ratio-transformers have an accuracy an order higher, about 0·01 per cent.

Before the Standards are checked, the following points should be noted. If high accuracy is required in measuring any component, all three decade controls must be in use. There is no requirement for these three controls to be checked to the same order of accuracy. Ignoring the decimal point and units, consider the reading 1234. The 1 is given by the first decade, the 2 by the second, and the figures 34 by the continuously-

variable control. The reading accuracy is within 0·1 per cent. If the Standard of the first decade is 0·1 per cent in error, the true value could be 1235 or 1233. The same effect would be caused by an error of 0·5 per cent in the second decade, or 3 per cent in the continuously-variable control.

The highest reading accuracy is obtained when all three decades are at maximum, giving a reading of 11110. With the Sensitivity control at maximum, a 1 per cent change in the continuous variable can be noticed. This corresponds to 0·1 per cent in the second decade and 0·01 per cent in the first decade. The highest accuracy is obtained, therefore, by adjusting the Standard in the first decade to 0·01 per cent, the Standard in the second to 0·1 per cent, and the continuously-variable control to 1 per cent. If this is done, the Bridge can often be used for measurements to an accuracy of 0·02 per cent, and almost always to 0·1 per cent.

One further point to be noted is that an aged Standard has a better long-term accuracy than a new one. Consequently, whenever possible the existing Standards should be adjusted by means of series or shunt elements in preference to being replaced.

CHECKING AND ADJUSTING STANDARDS

The absolute accuracy of the Bridge can be determined using only two external fixed Standards, one a resistor, the other a capacitor. As the Bridge Standards are themselves 0·1 per cent components, the reference Standards must be known with certainty to at least this degree of accuracy. The ideal reference Standards are a 0·01 per cent resistor of either 1000 or 10 000 ohms, and a 0·01 per cent capacitor of either 0·1 μF or 0·01μF. Using a reference of less than 1000 ohms (resistance or reactance) causes difficulty with the series impedance of the leads etc.; above 10 000 ohms trouble can arise from the spurious shunt elements. Even with a 0·01 μF Standard the connexions to the Bridge must be made carefully because 1 $\mu\mu F$ represents an error of 0·01 per cent, and this capacitance is produced by two inches of wire exposed outside the Neutral screen.

CONDUCTANCE STANDARDS

The procedure for checking the conductance Standards of the Bridge is described for a 1000-ohm external reference. If a 10 000-ohm reference is used, the Bridge range settings stated must be reduced by 1.

1 With the measurement leads and Neutral clip in position, and the *G* and *C* multipliers both set to 1, switch to Range 6, set all capacitance controls to zero, the two switched conductance decades to zero, but set the continuously-variable conductance control at 06.

2 Adjust the two Trim controls for exact balance with the Sensitivity control set fully clockwise. The reason for setting the variable control at 06 is to ensure that, when the Standard used in the first decade is checked, balance is possible without using the un-checked second decade, whether the Standard be slightly high or low.

3 Connect the 1$k\Omega$ reference resistor to the measurement leads and balance the Bridge by means of the *first* and *third* conductance controls only. To obtain a clean balance it may be necessary to adjust the Trim *C* control or to change the *C* multiplier switch setting to —1 and, after any necessary re-trimming, to operate the variable *C* control. If the exact point of balance lies between 1·005 and 1·007mMho, the first decade Standard is within the specified tolerance and no adjustment is necessary.

If balance does not occur within these limits, suitable series or shunt resistors should be added to the Standard in the Bridge. These resistors do not have to be close tolerance.

If it is desired to adjust the first decade Standard to 0·01 per cent, carry out the procedure described in 3a and 3b.

3a Disconnect the reference resistor and repeat steps 1 and 2 with the Range switch in position 5.

3b Re-connect the reference resistor, set the first conductance decade to 10 (⊕) and, if necessary, add series or shunt resistors to the first decade Standard until balance occurs between 1000·5 and 1000·7μMho. Adjust the *C* controls as described in para. 3.

4 Disconnect the reference resistor and repeat step 1.

5 Adjust the two Trim controls for exact balance with the Sensitivity control set fully clockwise.

6 Re-connect the reference resistor, set the second conductance decade to 10 (⊕) and balance the Bridge using the continuously-variable control. The exact point of balance should be between 1·005 and 1·007mMho. If necessary, add series or shunt resistors to the Standard of the second decade to bring the balance point within this range.

7 Set *all* decade controls at zero, disconnect the reference resistor and switch to Range 7. With the Sensitivity control fully clockwise, adjust the two Trim controls for a precise balance.

8 Re-connect the reference resistor and balance the Bridge. The reading should lie within half a scale division of the 10 calibration mark (1mMho). If outside this tolerance, set to 10 and balance the Bridge by adjusting the pre-set potentiometer *RV*5.

The calibration points 1 to 9 on the continuously-variable control can be checked quickly with a decade resistor box but this item is not essential. The alternative procedure is as follows.

9 Zero the Bridge on Range 3 and then set the first decade control to 1 (1·000μMho).

10 Connect the outer terminals of a 10*k*Ω potentiometer to the inner and Neutral respectively of the *E* measurement lead. Connect one end of a 100*k*Ω (20 per cent) resistor to the inner of the *I* measurement lead and the other end of this resistor to the wiper terminal of the potentiometer.

11 With the Sensitivity control set at mid-position, adjust the potentiometer to balance the Bridge.

12 Without disturbing the potentiometer adjusted in para. 11, change to Range 5, set the first decade to zero, and balance the Bridge using the continuously-variable control. Balance should occur within half a scale division of the 1 calibration mark.

Repeat the procedure described in paras. 9, 10, 11 and 12 with settings at 2, 3, etc. to 9. If desired, intermediate points can be checked by using both switched decades in para. 9.

By means of successive adjustments to the pre-set potentiometer *RV*5, it should be possible to bring the accuracy at all settings to within half a scale division. Any serious departure from this calibration is most likely to be due to a worn track on potentiometer *RV*2, in which instance it should be replaced. Play in the drive mechanism linking the potentiometer to the dial can also cause trouble. The degree of engagement between the racks and pinions can be adjusted by repositioning an eccentric cam.

CAPACITANCE STANDARDS

Succeeding paragraphs describe the procedure for checking the capacitance Standards of the Bridge, using a 0·1μ*F* external reference. If a 0·01μ*F* reference is used, the Bridge range settings stated must be reduced by 1.

1 With the measurement leads and Neutral clip in position, and the *G* and *C* multiplier switches both set to 1, switch to Range 6, set all conductance controls to zero, the two switched capacitance decades to zero, but set the continuously-variable capacitance control at 2(·002μ*F*).

2 Adjust the two Trim controls for exact balance with the Sensitivity control set fully clockwise. The reason for setting the variable control at 2 is to ensure that, when the Standard used in the first decade is checked, balance is possible without using the unchecked second decade, whether the Standard be slightly high or low.

3 Connect the 0·1μ*F* reference capacitor to the measurement leads and balance the Bridge by means of the *first* and *third* capacitance controls only. To obtain a clean balance it may be necessary to adjust the Trim *G* control. If the exact point of balance lies between ·1019 and ·1021μ*F*, the first decade Standard is within the specified tolerance and no adjustment is necessary.

If balance does not occur within these limits, remove *C*37 and replace it with a low-loss capacitor of suitable value.

If it is desired to check the first decade standard to 0·01 per cent, carry out the procedure described in 3a and 3b.

3a Disconnect the reference capacitor and repeat steps 1 and 2 with the Range switch in position 5.

3b Re-connect the reference capacitor, set the first capacitance decade to 10 (⊕) and, if necessary, make further changes to the value of *C*37 until balance occurs between ·10019 and ·10021μ*F*. Adjust Trim *G* if necessary.

4 Disconnect the reference capacitor and repeat step 1.

5 Adjust the two Trim controls for exact balance with the Sensitivity control set fully clockwise.

6 Re-connect the reference capacitor, set the second capacitance decade to 10(⊕) and balance the Bridge using the continuously-variable control and Trim *G*. The exact point of balance should be between ·1019 and ·1021μ*F*. If outside these limits, unseal trimmer *C*38 and adjust this component as necessary.

7 Set *all* decade controls at zero, disconnect the reference capacitor, and switch to Range 7. With the Sensitivity control fully clockwise, adjust the two Trim controls for a precise balance.

8 Re-connect the reference capacitor and balance the Bridge using the continuously-variable capacitance decade. The reading should lie within half a scale division of the 10 calibration mark (·1μ*F*). If outside this tolerance, first check that the racks and pinions are engaging properly and if necessary adjust the eccentric cam. The relative settings of the dial and variable capacitor can be altered slightly but, if this is done, *C*13 will have to be re-set as described in step 10.

9 Set *all* decade controls at zero, disconnect the reference capacitor, switch to Range 1 and, with the Sensitivity control set fully clockwise, adjust the two Trim controls for a precise balance.

10 Change the *C* multiplier switch position from 1 to 0·1 and to —1. The Bridge should remain balanced on all three positions. If it does not, unseal trimmer *C*13 and make a small adjustment. Repeat the process and adjust Trim *C* until the setting is found where balance is maintained on all three switch positions.

The calibration points 1 to 9 on the continuously-variable control can be checked quickly with a decade capacitor box but this item is not essential. The alternative procedure is as follows:

11 Zero the Bridge on Range 2 and then set the first capacitance decade control to 1 (10μμ*F*). Connect a variable capacitor, covering the range 10–90μμ*F*, to the measurement leads.

12 With the Sensitivity control set at mid-position, adjust the variable capacitor to balance the Bridge.

13 Without disturbing the variable capacitor, change to Range 4, set the first decade to zero and balance the Bridge using the continuously-variable control. Balance should occur within half a scale division of the 1 calibration mark.

Repeat the procedure described in paras. 11, 12 and 13 with settings at 2, 3, etc. to 9. If desired, intermediate points can be checked by using both switched decades in para. 11.

Should the calibration error exceed half a division at some points, adjustment should be made to the mechanism linking *C*11 to the dial. This adjustment *must* be followed by a repetition of the procedure described in paras. 9 and 10.

PHASE CORRECTION

Succeeding paragraphs describe firstly the adjustment of the two trimmer capacitors which off-set the slightly inductive properties of the two wire-wound conductance Standards and, secondly, the the adjustment of the pre-set potentiometer which controls the current compensating for the losses associated with the larger capacitance Standard.

1 Zero the Bridge on Range 4.

2 Select a 10*k*Ω *carbon* resistor slightly below the nominal value, so that balance is obtained with the first and last *G* decades only (the centre decade *must* remain at zero).

3 Adjust trimmer *C*16 to obtain a clean balance.

4 Change to Range 5, return the first decade to zero and set the second decade at 10 (⊕).

5 By means of the variable *G* decade and trimmer *C*36, obtain a clean balance.

The pre-set potentiometer *RV*1 is adjusted in the Test Department while a 3-terminal 10μμ*F* absolute Standard is connected to the Bridge. The potentiometer is not likely to need re-adjustment and, unless a capacitor of accurately-known power factor is available, the original potentiometer setting should not be disturbed.

If the external reference capacitor used for checking the decades has a tolerance of 0·01 per cent, the power factor will probably be quoted (at 1000c/s). This factor will be virtually unchanged at 1592c/s. The capacitor could be used, therefore, to check the setting of *RV*1.

PARALLEL TO SERIES CONVERSION

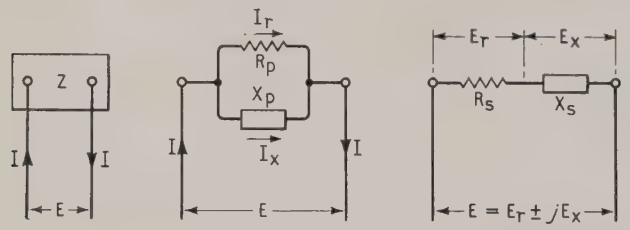
THEORY

Impedance is defined by Ohm's Law as $Z=E/I$, the ratio of a voltage to a current. If the impedance is complex, the voltage-to-current ratio also must be complex and E or I must have two components. If the voltage is chosen as a reference, the current must have the form $I_r \pm jI_x$, where I_r is in phase with E and I_x in quadrature. If the current is chosen as a reference, the voltage must have the form $E_r \pm jE_x$, where E_r is in phase with I and E_x in quadrature. There are, therefore, two distinct but equivalent ways of representing a given complex impedance.

In section (a) of Fig. 22, the impedance Z between the terminals is given by the ratio E/I. In (b) the impedance is shown as resistive and reactive components in parallel. The voltage, E, is a reference and the current, I, consists of two components, $I_r \pm jI_x$. The third part of the illustration, (c), shows the alternative representation as a series circuit, where the current is the reference. The potential developed across the terminals is complex and is given by $E=E_r \pm jE_x$. Because both series and parallel arrangements represent the same impedance, the components are mathematically related:

$$R_s=R_p/(1+Q^2) \qquad R_p=R_s(1+Q^2)$$
$$X_s=X_p/(1+1/Q^2) \qquad X_p=X_s(1+1/Q^2)$$

where $Q=X_s/R_s=R_p/X_p$, and $X=\omega L$ or $1/\omega C$. ($\omega=10^4$).



(a) (b) (c)

Fig. 22. Equivalent Series/Parallel Circuits

DETERMINATION OF Q

The Q-factor of a component can be calculated directly from the numerical readings presented by the decade controls without reference to the Range in use, the units of measurement or the position of the decimal point. Q is always equal to the ratio of the numerical reading on the C decades to that on the G decades. For example, if balance is obtained on Range 4 with ·000625μ*F* and 12·50μ*mhos* (where the digits underlined are those *presented by the decade controls*—first C decade at zero in this example) then, ignoring the decimal point, $Q=0625/1250=0{\cdot}5$. If the C multiplier switch is on 0·1, the reading on the C decade must be divided by ten before Q is computed.

APPLICATION

Because the Bridge measures the effective parallel components of conductance and capacitance rather than resistance and reactance, the formulae given below are more useful than the usual form given in the Theory section. Equivalent series components are given by:

$$R_s=1/[G_p(1+Q^2)]$$
$$C_s=C_p(1+1/Q^2)$$
$$L_s=1/[\omega^2 C_p(1+1/Q^2)].$$

G_p and C_p are the Bridge readings of the equivalent parallel components and Q can be derived as described in the previous section. $\omega^2=10^8$. From the last two equations it can be seen that if $Q \gg 1$, $C_s \simeq C_p$ and $L_s \simeq 1/\omega^2 C_p$. Tables of reciprocals are provided at the back of this Handbook and a quick check on the position of the decimal point may be made by referring to the table of decade equivalents (below).

TABLE 5 DECADE EQUIVALENTS

G	·001μmho	·01μmho	0·1μmho	1μmho	10μmho	100μmho	1m.mho	10m.mho	100m.mho
R	1000MΩ	100MΩ	10MΩ	1MΩ	100kΩ	10kΩ	1kΩ	100Ω	10Ω

C	0·1μμF	1μμF	10μμF	100μμF	·001μF	·01μF	0·1μF	1μF	10μF
L	100kH	10kH	1000H	100H	10H	1H	100mH	10mH	1mH

Part 2 - Low Impedance Adaptor Q221

INTRODUCTION

The lower limit of impedance measurement that can be made accurately with the Universal Bridge is determined by lead resistance and the winding resistance of the Bridge transformers. The Low Impedance Adaptor, designed to operate in conjunction with the Bridge, extends the range of measurement to include large values of capacitance and very small values of resistance and inductance.

Measurements with the Bridge itself are of the equivalent *parallel* components of conductance and capacitance, obtained by applying a reference potential to the Unknown and measuring the resulting current. The function of the Adaptor is to reverse the procedure to one of passing a reference current through the Unknown and measuring the resulting voltage. This reversal is achieved with a resistive *T*-network where the shunt arm consists of the Unknown. The required value is derived very simply from the Bridge dial-readings in terms of the equivalent *series* components of resistance and inductance.

The prime function of the Adaptor is to permit measurements on impedances of less than ten ohms to be made *with the first decade switches set permanently to zero.* Under these conditions the value of the Unknown has a negligible effect on the reference current and measurements are of the specified accuracy. Only when absolute accuracy is a secondary consideration to the detection of small changes should the first decade be used. The usefulness of very fine discrimination and measurements from 10 to 100 ohms are discussed in the *Q*221 Appendix.

SPECIFICATION

Resistance Ranges*	1	0—10$m\Omega$	Discrimination 0·2 per cent of maximum Accuracy ±1 per cent ±25$\mu\Omega$
	2	0—100$m\Omega$	
	3	0—1Ω	
	4	0—10Ω	
Impedance Ranges	As above		
Inductance Ranges*	1	0—1μH	Discrimination 0·2 per cent of maximum Accuracy ±1 per cent ±0·005μH
	2	0—10μH	
	3	0—100μH	
	4	0—1mH	
Capacitance Ranges*	1	∞—100 00μF	Accuracy dependent on precise knowledge of Bridge frequency.
	2	∞—1000μF	
	3	∞—100μF	
	4	∞—10μF	
Dimensions	Base diameter		$5\frac{1}{16}$in. (12·9cm).
	Height		$3\frac{5}{16}$in. (8·5cm).
Packed Weight	Not exceeding		$5\frac{1}{2}$lb (2·5kg).

* The ranges quoted are those obtained with the first *G* and *C* decade switches at zero (see Q221 Appendix– Discrimination and Accuracy). With all three decades in use, the ranges are extended by a factor of 10 to the values shown on the Adaptor range plate.

GENERAL

The Adaptor assembly consists of a cylindrical case fitted to a circular brass base. These contain a four-way switch and the associated Standards, A terminal block, provided for two-terminal measurements, is housed between spring clips underneath the Adaptor. Two cables from the base of the Adaptor are terminated in coaxial sockets for connexion to the Universal Bridge. The recessed plugs on top of the Adaptor provide connexion to the terminal block, either directly or via the extension leads supplied with the Adaptor. When four-terminal measurements are being made, the clip leads supplied with the Bridge are used.

PRINCIPLE OF OPERATION

Refer to Fig. 23. When the Bridge is balanced, the voltage across the current transformer winding is, for all practical purposes, zero. Resistor R_2 is therefore effectively in parallel with the Unknown, Z_u. If the value of R_2 is very high compared with Z_u, the shunting effect is negligible and can be ignored. The current through the Unknown is then equal to $E/(R_1+Z_u)$. If R_1 also is made very high compared with Z_u, the effect of Z_u on the current is negligible and can be ignored.

With these two approximations:

current through the Unknown,

$$i = E/R_1$$

voltage across the Unknown,

$$e=Z_u \cdot E/R_1$$

current fed back to Bridge,

$$I=e/R_2=Z_u \cdot E/R_1R_2.$$

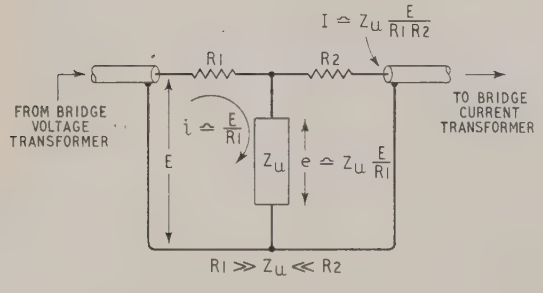


Fig. 23. Principle of Operation

For convenience, R_1 and R_2 are made equal, so that:

$$R_1=R_2=R$$

and

$$I=Z_u \cdot E/R^2$$

or

$$Z_u=R^2 \cdot I/E \quad \ldots\ldots\ldots (1)$$

The current I flows in the Bridge current transformer and E is the potential provided by the voltage transformer. The ratio I/E is therefore the admittance represented by the Bridge dial readings at balance. The value of the Unknown impedance is obtained (using equation 1) by multiplying the admittance read off the Bridge by R^2 and translating mhos as ohms. By making R^2 a suitable multiple of 10, the system becomes direct-reading.

It was assumed above that the value of the series resistors of the T-network was so high compared with the Unknown impedance that their shunting effect could be ignored. The balance equation is:

$$R^2/Z_u + 2R=1/(G_b+j\omega C_b)$$

where G_b and C_b are the conductance and the capacitance values read from the Bridge dials. The approximations made in the derivation of equation (1) are based on the assumption that $|R^2/Z_u|$ is much greater than $2R$. This approximation is valid *provided that the first decades are not used.*

CIRCUIT DESCRIPTION

A circuit diagram is provided at the end of this Handbook. Four pairs of equal-value resistors form the switched series elements of a *T*-network. For most measurements the Blue and White plugs are connected in parallel by the terminal block. The shunt arm of the network is then completed when the Unknown is connected between their inners and Neutral.

The series resistance of each arm is, for the four ranges, $\sqrt{10^4}$, $\sqrt{10^5}$, $\sqrt{10^6}$ and $\sqrt{10^7}$ ohms. The resistors in the Adaptor have slightly lower values to allow for the resistance of connecting leads and the Bridge transformer windings. The capacitors correct the small phase-shift introduced by the leakage inductance of these transformers.

The terminal block consists of two metal plates, insulated from each other, the upper bearing two terminals. Both Neutral leads ('Blue' and 'White') are connected to the lower plate and *both* inner leads are connected to the upper plate. The two Neutrals are automatically linked, therefore, whenever the terminal block is in use. The insulated terminal is Neutral and is connected to the lower plate by a short piece of studding that passes through an insulating bush. This construction ensures that contact resistance and mutual coupling are kept to a minimum.

As stated in the Introduction, the function of the Adaptor is to reverse the method of measurement as compared with the Bridge. Thus the Blue plug of the Adaptor, although associated with the *E* plug of the Bridge, serves to feed a constant *current* to the Unknown. Similarly the White plug of the Adaptor feeds back a voltage to the Bridge.

OPERATING INSTRUCTIONS

GENERAL PROCEDURE

1 Connect the Adaptor to the Bridge: the cable with a blue sleeve to the *E* plug and that with a white sleeve to the *I* plug. Do *not* clip the shorting bar across these connectors. The two Neutrals are linked at the Adaptor terminal block.

2 Fit the terminal block (housed between spring clips underneath the Adaptor) on to the recessed plugs on top of the Adaptor. (Alternative methods of measurement are described under 'Connexion to the Unknown').

3 Set the Range switch on the Universal Bridge to position 3 (the Range number appears between the two magic eyes).

4 Set all Bridge dials to zero.

5 Set the *G* and *C* selector switches to 1.

6 Set the Adaptor to Range 4.

7 Short-circuit the Adaptor terminals with the link provided, or with a piece of heavy-gauge wire.

8 Balance the Bridge, using the Trim *G* and Trim *C* controls.

9 Remove the shorting link from the terminals. The Adaptor is now ready for use.

10 Select the required range on the Adaptor. Do not alter the range on the Bridge: this must *always* be 3 when the Adaptor is in use.

11 Connect the Unknown to the terminals and balance the Bridge using the continuously-variable and second decade controls only. Use the Adaptor always on the highest range that provides satisfactory reading accuracy. Succeeding paragraphs describe in detail the procedure for measuring the various types of impedance, but the settings of the *G* and *C* selector switches can be summarized as:

both at 1 for *R* and *L*,

G at 1 and *C* at —1 for *R* and *C*,

either or both at —1 for mutual or transfer impedance.

MEASUREMENT OF RESISTANCE

Follow the general procedure given in the previous section. In step 11, with the component to be measured connected across the terminals, set the *G* and *C* selector switches to 1. From equation (1) under Principle of Operation, the Unknown is given by:

$$R_u = R^2 \,.\, G$$

where R^2 is the scale multiplying factor given on the Adaptor range plate (reproduced in Fig. 24) and G is the conductance value shown on the Bridge dials.

Example:
Adaptor on Range 2.
Bridge reading 0·337μ*Mho*.
Adaptor range plate: $\Omega = \mu Mho/10$

$= 0{\cdot}337/10$

or $R_u = 0{\cdot}0337$ ohm.

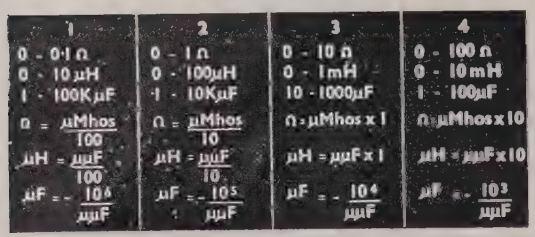

1
0 - 0·1 Ω
0 - 10 μH
1 - 100K μF
Ω = μMhos / 100
μH = μμF / 100
μF = 10^6 / μμF
2
0 - 1 Ω
0 - 100 μH
1 - 10K μF
Ω = μMhos / 10
μH = μμF / 10
μF = 10^5 / μμF
3
0 - 10 Ω
0 - 1 mH
10 - 1000 μF
Ω = μMhos x 1
μH = μμF x 1
μF = 10^4 / μμF
4
0 - 100 Ω
0 - 10 mH
1 - 100 μF
Ω = μMhos x 10
μH = μμF x 10
μF = 10^3 / μμF

Fig. 24. Adaptor Range Plate

MEASUREMENT OF INDUCTANCE

Proceed as for Measurement of Resistance. From equation (1), under Principle of Operation,

$$j\omega L_u = R^2 \cdot j\omega C$$

or $L_u = R^2 \cdot C$

where R^2 is the scale multiplying factor given on the Adaptor range plate and C is the capacitance value shown on the Bridge dials.

Example:
Adaptor on Range 4.
Bridge reading 64·8μμ*F*.
Adaptor range plate: $\mu H = \mu\mu F \times 10$

$= 64{\cdot}8 \times 10$

or $L_u = 648\mu H$.

MEASUREMENT OF CAPACITANCE

Proceed as for Measurement of Resistance but with the C selector switch at —1. From equation (1), under Principle of Operation,

$$1/j\omega C_u = R^2 \cdot j\omega C$$

or $$C_u = -1/(\omega^2 \cdot R^2 \cdot C)$$

where C is the capacitance value shown on the Bridge dials. The operating frequency of the Bridge is 1592c/s so that ω^2 is 10^8. The term $\omega^2 \cdot R^2$ is incorporated in the scale multiplying factor given on the Adaptor range plate. The value of C_u can, however, be found directly from the conversion chart at the end of this Handbook.

Example:
Adaptor on Range 4.
Bridge reading —17·4μμ*F*.
Adaptor range plate: $\mu F = -10^8/\mu\mu F$

$= -1000/-17{\cdot}4$

or $C_u = 57{\cdot}5\mu F$.

Note: *The scale multiplying factor for capacitance (on the Adaptor range plate) applies* only *to a B221 Bridge operating at* 1592 *c/s.*

MEASUREMENT OF COMPLEX IMPEDANCE

Follow the General Procedure: there is no interaction and the resistive and reactive components balance independently. The equivalent *series* components are obtained by combining the values calculated according to the appropriate measurement paragraphs. If the Unknown is required in the form $R \pm jX$, the reactive term can be obtained very simply from the corresponding L or C component ($\omega = 10^4$). An alternative method is described in the next section.

MEASUREMENT OF REACTANCE

The Bridge is so designed that the resistive and reactive scales cover the same range in ohms. If on a particular range of the Adaptor the Bridge G dials cover 0 to 1 ohm, the C dials, therefore, cover 0 to 1 ohm also. Assuming the Bridge has been balanced, the procedure for measuring reactance directly in ohms is as follows.

Mentally transfer the figures on the C dials to the G dials (so that the last digits are coincident) and insert in this transferred reading a decimal point where one occurs on the G dials. Apply to this amended reading the scale multiplying factor for ohms given on the Adaptor range plate. The result is the required reactance value.

Example:
Adaptor on Range 4.
Bridge reading 0·362μ*Mho* and 117·4μμ*F*.
If the figures that appear on the C dials (giving the reading 117·4μμ*F*) had appeared on the G dials, the reading would have been 1·174μ*Mho*. This is seen by writing them underneath in corresponding positions:

0·362μ*Mho* (actual reading on G scale)

1·174μ*Mho* (figures mentally transferred from C scale).

The range plate on the Adaptor gives

$$\Omega = \mu Mhos \times 10$$

giving for the resistance term

$$R_u = 0{\cdot}362 \times 10$$
$$= 3{\cdot}62 \text{ ohms}$$

and for the reactance term

$$X_u = 1{\cdot}174 \times 10$$
$$= 11{\cdot}74 \text{ ohms.}$$

CONNEXION TO THE UNKNOWN

It was assumed in the General Procedure that components being measured could be connected between the two screw terminals. The terminal block can be connected either directly to the plugs on top of the Adaptor or to these plugs through the extension leads provided. Where direct connexion to the terminals is not possible, short heavy-gauge leads from the component to the terminals may be used. Alternatively, the clip leads supplied with the Bridge can be fitted to the top of the Adaptor: this method is discussed in succeeding paragraphs. In *all* methods of measurement, the Trim controls should be adjusted with a short-circuit applied across the terminals of the Unknown.

When very low values of impedance are to be measured *in situ*, some precautions must be observed or large errors may arise. Two faults are indicated by the left-hand illustration of Fig. 25. Firstly, if the two cables are arranged side-by-side and large loops formed at their ends, there is considerable danger that the reference current in one loop may induce a sufficiently large voltage in the other to cause a significant error. Secondly, the voltage being measured is not only the potential drop across Z_u but also that occurring in the leads from Z_u to the point of contact of the current clips.

In this respect it must again be emphasized that the lead coded blue, from the Adaptor to the Unknown, although associated with the *E* plug of the Bridge is effectively the CURRENT lead from the Adaptor. Similarly, the function of the white (*I*) lead is to feed back to the Bridge the VOLTAGE measured across the Unknown.

The areas of the loops involved in the connexions should be kept as small as possible and the coupling between them made as low as possible. This is shown diagrammatically in the right-hand illustration of Fig. 25, which shows also the correct positioning of the current clips outside the voltage clips. These connexions must be made independently on to the leads from the Unknown: the clips must not touch and one set must never be used as a connexion for the other.

ADJUSTMENT OF THE TRIM CONTROLS

As described in previous sections, the Trim controls are adjusted with the Adaptor switched to Range 4 and all Bridge controls set to zero. Such adjustment will hold when the Adaptor is used also on Ranges 3 and 2 and, for most purposes, the slight loss of trim on Range 1 can be ignored. For accurate *in-situ* measurements of very low impedances, however, it is advisable to re-check the trim on Range 1, with the leads disposed as they will be for the actual measurement. The clips should be attached to a short piece of heavy-gauge wire.

ERRORS IN THE MINOR COMPONENT

It must be realised that inaccuracies may occur when measuring the minor component of a complex impedance whose resistive and reactive elements are very different in magnitude at 1592 c/s. (It may be noted that a minor component of 0·1 per cent affects the modulus of the impedance by less than one part in a million.) The Adaptor is not suitable for accurate measurements on small minor components, but a reliable approximation can be obtained if great care is taken in the adjustment of the Trim controls and the leads are disposed for minimum coupling

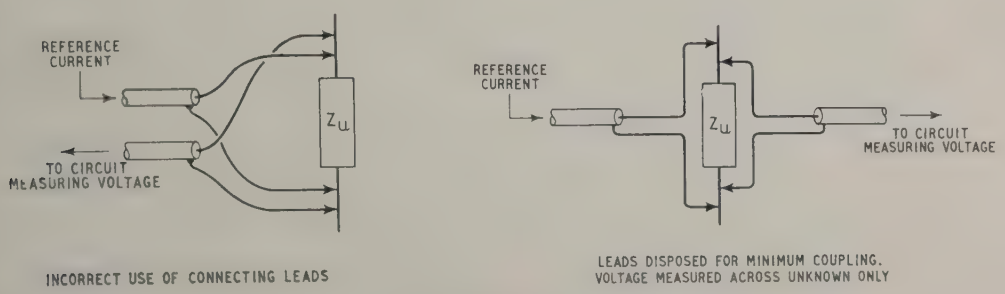


Fig. 25. Connexion to the Unknown

and for minimum disturbance when the short-circuit is removed from the Unknown.

A correction to allow for the residual reactance of the Adaptor can be made as follows. The measured values of the resistance and reactance of the Unknown are first obtained in the usual manner. The Unknown is then replaced by a carbon resistor of near value to the resistance of the Unknown, using the shortest possible connexions from the terminals or clips. The resistance and apparent reactance of this resistor are measured. As a carbon resistor has a totally insignificant reactive term at the Bridge frequency, the reactance must be due to the Adaptor or Bridge circuits. In both measurements a note must be made of the sign of the reactance (positive for inductive and negative for capacitive). The true reactance of the Unknown is given by:

(Apparent reactance of Unknown)—(Apparent reactance of carbon resistor).

This true value of reactance can be converted into the corresponding inductance or capacitance from the appropriate expression:

$$L = (\text{True reactance})/10^4,$$

$$\text{or } C = 1/(10^4 \times \text{True reactance}).$$

MEASUREMENT OF R.F. COILS

It must be borne in mind that, although measurements can be made in the millimicrohenry region, the Adaptor is not ideally suited to the measurement of r.f. and v.h.f. coils. This is because skin effect and self-capacitance result in the inductance at the operating frequency of the coils being very different from the value at 1592c/s. The change is dependent upon so many factors (geometry, wire size, spacing, type of insulation, effect of screening and so on) that no useful extrapolation can be made. Furthermore, air-cored coils of small inductance behave, at audio frequencies, like slightly inductive resistors, so that accurate measurement of a minor component would be required.

The Adaptor is useful for comparison measurements and for obtaining the coupling coefficients of i.f. transformers, sections of delay line, etc. Also, in v.h.f. circuits a large proportion of the circuit inductance is contained, often, in the wiring and switches. The geometry in such instances makes possible reasonably accurate measurements using the Adaptor and, in fact, the value of such inductance is difficult to ascertain otherwise because the measurement must be made *in situ*.

MEASUREMENT OF MUTUAL INDUCTANCE

The method of connecting a transformer is illustrated in Fig. 26, where the two resistors are the Standard components in the Adaptor. Assuming that the loading imposed by the secondary R is insignificant and that the self-impedance of the primary is so low that it has no effect on the current, the current through the primary will be

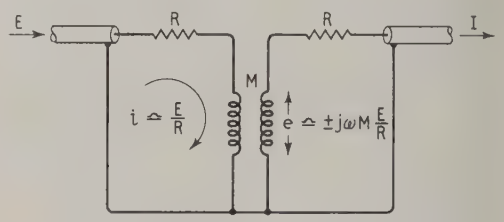


Fig. 26. Measurement of Mutual Inductance

given by E/R. This will induce into the secondary a voltage of $\pm j\omega M \,.\, E/R$, where the sign is determined by the relative sense of the windings. At balance the induced voltage will drive a current, $\pm j\omega M \,.\, E/R^2$, through the current transformer of the Bridge. From equation (1), under Principle of Operation,

$$\pm j\omega M = R^2 \,.\, I/E.$$

Replacing I/E by the equivalent on the Standards side of the Bridge:

$$j\omega M = \pm j\omega C \,.\, R^2$$

$$\text{or } M = \pm C \,.\, R^2.$$

Mutual inductance is read, therefore, in the same manner as self-inductance, the alternative signs being catered for by the 1 and —1 positions of the C selector switch. The setting required depends on the relative sense of the two windings.

POLARIZING ELECTROLYTIC CAPACITORS

When it is considered necessary to prevent a reverse polarity (caused by the small a.f. measuring

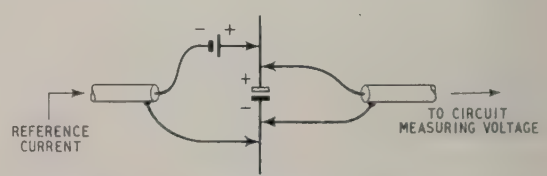


Fig. 27. Polarizing Electrolytic Capacitors

voltage) from appearing across an electrolytic capacitor, a polarizing potential of one or two volts from for example a single dry cell can be applied as shown in Fig. 27. Under no circumstances should a high polarizing voltage be used.

ACCUMULATOR RESISTANCE

The Low Impedance Adaptor can be used for certain measurements on accumulators. A limitation is imposed by the permissible d.c. through the Adaptor resistors. These have a continuous rating of 0·5 watt. The maximum values of d.c. voltage that may be applied to the *Adaptor* terminals (these values *must not* be applied directly to the Bridge), and the corresponding current values, are given below.

Adaptor Range	Maximum d.c. Voltage	Maximum Direct Current into Adaptor
1	7V	140 mA
2	12V	80 mA
3	22V	45 mA
4	40V	25 mA

It must be realised that the measurement will be of the impedance of the accumulator, consisting of a resistance in series with a small reactive component.

MAINTENANCE AND SERVICE

A circuit diagram of the Adaptor is provided at the back of this Handbook. The Bridge itself may be used to check the values of the Adaptor components. The switch and all plugs and sockets must be maintained in good order.

Q221 APPENDIX

DISCRIMINATION AND ACCURACY

The Low Impedance Adaptor serves merely as an impedance invertor between the Bridge and the Unknown, measurement being made on the Bridge itself. This has two decade switches and a continuously-variable control on each component and is consequently capable of a discrimination of 0·02 per cent. Such a high discrimination extended to the Adaptor ranges can be useful for comparison of component values or the detection of small changes such as in temperature coefficient measurements. This order of discrimination is obtained only when the first decades are in use and, in these circumstances, the approximations referred to under 'Principle of Operation' are not justified. Absolute values cannot be derived with an accuracy of 1 per cent, therefore, using the simplified formulae, but can be calculated from the balance equation:

$$R^2/Z_u + 2R = 1/(G_b + j\omega C_b).$$

It may be found more convenient to make an absolute measurement without using the first decades and employ this as a reference for subsequent comparisons where increased discrimination is important.

From the foregoing considerations it follows that Range 4 of the Adaptor should be used for measurements up to only 10 ohms if maximum absolute accuracy is required. Above this value the Bridge should be used. Where high discrimination between values of resistance is essential and the first decades are used, the true value can be found either from the balance equation or by reference to the correction curves given at the end of this Handbook.

If an unstable value of impedance, such as the resistance of a defective switch contact, is to be measured, only an approximate reading is necessary. The continuously-variable controls alone should be used to obtain balance. If the switched decades are operated, the discrimination may be such that the random drift in resistance occurs more rapidly than the controls can be adjusted, making balance impossible.

CURRENT THROUGH THE UNKNOWN

The absolute value of alternating current passing through the Unknown cannot be specified accurately: the Bridge measurements are obtained by comparison. The values given are, therefore, approximate.

Adaptor Range	R.M.S. Current through Unknown
1	8mA
2	5mA
3	2mA
4	0·7mA

B221 MODIFICATION (50c/s - 20kc/s)

GENERAL

In order to provide facilities for measuring impedances at frequencies other than 1592c/s, the Universal Bridge has been modified to allow an external source and detector to be connected to the instrument. Details of the performance required of such external equipment, the accuracy obtainable using frequencies from 50c/s to 20kc/s, and the revised operating procedures, are detailed in the following paragraphs.

B221 ALTERATIONS

Two connectors have been mounted on the rear of the chassis and circular cut-outs in the case, normally closed with button-covers, provide access to these. When the instrument is viewed from the front, the *right-hand* socket is that connected to the primary of the voltage transformer (*T*1) and is the input point for an external source. The *left-hand* socket provides an output from the secondary of the current transformer (*T*2) for feeding to an external detector. Two 4-ft screened leads are provided, each fitted with a suitable connector at one end and unterminated at the other.

EXTERNAL SOURCE

This should be capable of providing an output of 10–30V r.m.s. into an impedance of approximately $20k\Omega$. The larger output is required at low frequencies but the input to the Bridge must never exceed 40V r.m.s. The frequency coverage required depends on the types of measurement to be made, but satisfactory operation with the Bridge is obtained from 50c/s to 20kc/s. The output should have a low harmonic content and *any d.c. component must be blocked externally.*

EXTERNAL DETECTOR

This must operate satisfactorily from an input falling to 10–20μV near balance and should have an input impedance of not less than $100k\Omega$. It is essential to employ a tuned amplifier, adjusted to the same frequency as the source, as this minimizes the effect of harmonics masking the point of balance at the required frequency. When measurements are made at the lowest frequencies (50c/s—200c/s) the sensitivity required is 1 to 5 microvolts. In general, it is preferable to use a high-gain detector to obtain the required sensitivity, rather than to increase the source voltage.

OPERATION AT 1592c/s

When the facility of using an external source and detector is not required, no connexions must be made to the rear of the Bridge and the apertures should be closed with the button-covers provided. Normal operation of the instrument is then obtained at 1592c/s (or 1kc/s where the Bridge is supplied for operation at this frequency).

OPERATION AT OTHER FREQUENCIES

When the Bridge is to be operated with an external source and detector it must first be disconnected from the a.c. mains supply. The two button-covers at the rear of the case should be removed to provide access to the detector (*D*, left-hand side when the instrument is viewed from the front) and source (*S*) connectors. The unterminated ends of the two 4-ft screened leads should be provided with connectors to suit the external source and detector. Wayne Kerr Audio Signal Generator S121 is a suitable source and Waveform Analyser A321 can be used as a detector. If the source output includes a d.c. potential, this must be blocked externally. The two external equipments should be connected to the Bridge, the source adjusted to the desired frequency, and the detector tuned for maximum output at this frequency. The Bridge is then operated in the normal manner.

MEASUREMENT ACCURACY

400c/s—5kc/s: Better than $\pm 0{\cdot}5$ per cent.

50c/s—400c/s and 5kc/s—20kc/s: Better than ± 1 per cent.

The accuracy of the Bridge remains at $\pm 0{\cdot}25$ per cent when used without external source or detector (i.e. when operated at 1592c/s or 1kc/s).

The figures quoted are for the basic measurements of conductance and capacitance. Evaluation of inductance and certain measurements with the Low Impedance Adaptor are dependent on a precise knowledge of the source frequency: the procedure in such instances is given later.

In the whole of the frequency band, it must be borne in mind that the Bridge will not measure resistance, reactance, or a combination of both, if the value is less than 10 ohms. When this value is approached, and generally if the Bridge is operated on Range 6 or 7, a correction to the result must be made to allow for the series resistance and

leakage inductance of the Bridge transformers and for the resistance and inductance of connecting leads. This has been described on page 19.

BRIDGE/ADAPTOR CHANGE-OVER

The maximum conductance (minimum resistance) that can be measured on the Bridge is 100 millimhos at all frequencies. In the case of capacitance and inductance, however, the limiting values are determined by the frequency of measurement.

At the lower frequencies the maximum capacitance is 10 microfarads. This determines also the minimum inductance than can be measured at any given frequency (since $L=1/\omega^2C$).

At higher frequencies (above 1592c/s) there is a maximum value of capacitance than can be measured (on the Bridge) before its reactance falls below 10 ohms. With this value of capacitance, there is also a minimum value of inductance that can be measured. The table provides a guide to these values at selected frequencies in the band.

Source Frequency	Maximum Capacitance	Minimum Inductance
50c/s	10μF	1H
60c/s	10μF	0·7H
100c/s	10μF	250mH
200c/s	10μF	63mH
400c/s	10μF	16mH
800c/s	10μF	4mH
1000c/s	10μF	2·5mH
1592c/s	10μF	1mH
2kc/s	8μF	0·8mH
4kc/s	4μF	0·4mH
8kc/s	2μF	0·2mH
10kc/s	1·6μF	0·16mH
15kc/s	1μF	0·11mH
20kc/s	0·8μF	0·08mH

SHUNT LOADING

When the Bridge is used on Range 1 or 2 (for the measurement of large values of resistance and/or reactance) at frequencies above 2000c/s, particular care must be taken to avoid heavy shunt loading to the Neutral from either the voltage or current leads. If such loading is present, the measured value of the Unknown should be corrected using the formulae given on page 17.

LOW IMPEDANCE ADAPTOR

Resistances of less than 10 ohms are measured on the Low Impedance Adaptor in the normal manner.

Inductances of less than $1mH$ (or $10mH$ if the first decade control is operated) are measured on the Low Impedance Adaptor. When the value exceeds $1mH$ (or $10mH$) the measurement can be made with the Bridge alone provided that a sufficiently high frequency is employed (see table).

Capacitances whose reactance falls below 10 ohms at any one frequency (the dividing line is indicated in the above table) are measured with the Low Impedance Adaptor but the relationships for capacitance, given on the Adaptor range plate, do *NOT* apply at any frequency except 1592c/s. The value of the unknown capacitance is given by the expression

$$C_u=-1/(\omega^2R^2C_b).$$

At a frequency of 1592c/s ($\omega=10^4$) the above expression can be simplified to give the scale multiplying factors for capacitance shown on the Adaptor range plate. These same four factors can be used for computing the measured capacitance at other frequencies if the result is multiplied by a suitable constant (K). This is equivalent to re-writing the above expression as:

$$C_u=K[-1/(\omega_o^2R^2C_b)]$$

where $\omega_o=2\pi\times1592$ and $K=(\omega_o/\omega)^2$.

The value of K at selected frequencies between 50c/s and 20kc/s is shown in the table (below).

Measurement Frequency	K	Measurement Frequency	K
50c/s	1015	1592c/s	1·00
60c/s	704	2kc/s	0·634
100c/s	254	4kc/s	0·158
200c/s	63·4	6kc/s	0·0704
400c/s	15·8	8kc/s	0·0397
600c/s	7·04	10kc/s	0·0254
800c/s	3·97	12kc/s	0·0176
1000c/s	2·54	15·92kc/s	0·01
1200c/s	1·76	20kc/s	0·0063

Example

With the range multiplier switches set at $1(G)$ and $-1(C)$, balance was obtained on Range 3 of the Adaptor with a capacitance dial reading of $-74{\cdot}1\mu\mu F$.

The measurement frequency was 800c/s.

From the Adaptor range plate:

$$\mu F = -10^4/\mu\mu F \text{ (at 1592c/s)}$$

$$= K[-10^4/\mu\mu F] \text{ at 800c/s.}$$

From the table, K at 800c/s is 3·97.

$$\therefore C_u = 3{\cdot}97\ [-10^4/-74{\cdot}1]\mu F$$

$$= 3{\cdot}97 \times 135\mu F$$

$$= 536\mu F.$$

With a Bridge dial reading of $10\mu\mu F$, the maximum values of capacitance that can be measured at a frequency of 400c/s are:

Adaptor Range 1	1·58 Farads
Adaptor Range 2	158 000μF
Adaptor Range 3	15 800μF
Adaptor Range 4	1580μF.

The range of capacitance measurement is further extended by the use of lower measurement frequencies. Also, if the Bridge dial reading at balance is less than $10\mu\mu F$, the measured capacitance is of a very high value. Such measurements are obtained with reduced sensitivity and accuracy.

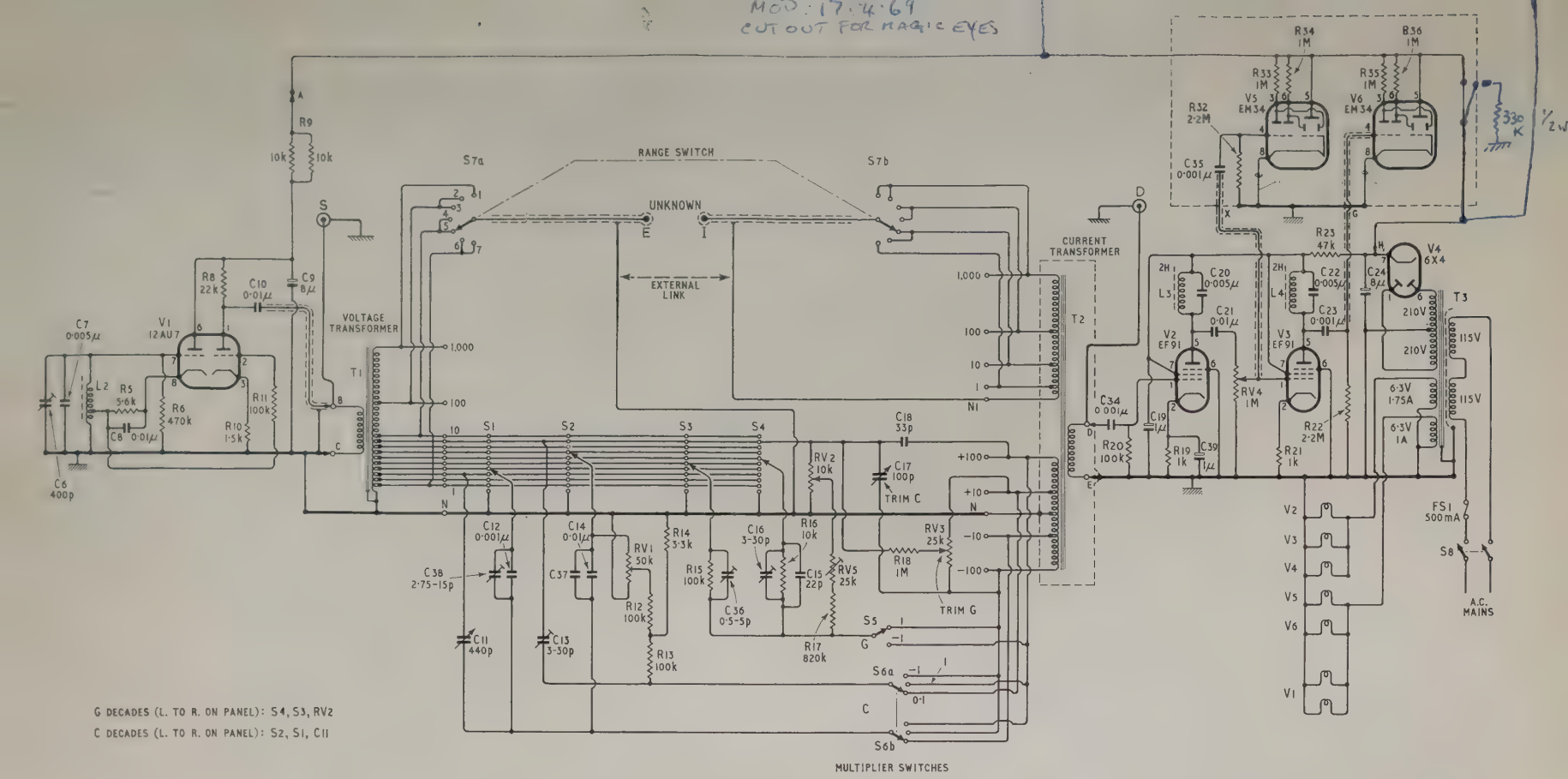
When very large values of capacitance are measured, the inductance of connecting leads becomes of extreme importance and must be kept to the absolute minimum. For example if a capacitor of 200 000μF is measured at 1kc/s, a lead inductance of only $\frac{1}{8}\mu H$ will resonate with the capacitor. Even $\frac{1}{80}\mu H$ will cause a 10 per cent error in the measured capacitance value.

Note: *ALL measurements with the Low Impedance Adaptor* must *be made with the Bridge on Range 3. At all frequencies the results are derived from the simplified formulae (used in preceding paragraphs) only if the first decades of the Bridge are at zero (see Q221 Appendix—Discrimination and Accuracy).*

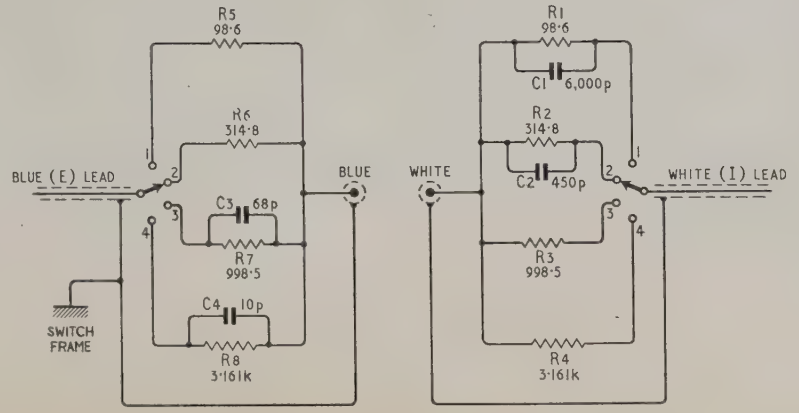
B221 COMPONENT LIST

Ref.	Value	Tolerance (per cent)
R1–R4	Not used	
R5	5·6 kΩ	±10
R6	470 kΩ	±10
R7	Not used	
R8	22 kΩ	±10
R9	10 kΩ } Two in	±10
R9	10 kΩ } parallel	±10
R10	1·5 kΩ	±10
R11	100 kΩ	±10
R12	100 kΩ	±10
R13	100 kΩ	±10
R14	3·3 kΩ	±10
R15	100 kΩ	±0·1
R16	10 kΩ	±0·1
R17	820 kΩ	±1
R18	1 MΩ	±1
R19	1 kΩ	±10
R20	100 kΩ	±10
R21	1 kΩ	±10
R22	2·2 MΩ	±10
R23	47 kΩ	±10
R24–R31	Not used	
R32	2·2 MΩ	±20
R33	1 MΩ	±10
R34	1 MΩ	±10
R35	1 MΩ	±10
R36	1 MΩ	±10
RV1	50 kΩ	Linear
RV2	10 kΩ	Lin. to ½ per cent
RV3	25 kΩ	Linear
RV4	1 MΩ	Log
RV5	25 kΩ	Linear
FS1	500 mA	

Ref.	Value	Type
C1–C5	Not used	
C6	400 μμF	Trimmer
C7	5000 μμF	±2 per cent
C8	0·01 μF	350 V
C9	8 μF	350 V
C10	0·01 μF	350 V
C11	440 μμF	Variable
C12	0·001 μF	+0, —0·5 per cent
C13	3—30 μμF	Trimmer
C14	0·01 μF	+0, —0·5 per cent
C15	22 μμF	±10 per cent
C16	3—30 μμF	Trimmer
C17	100 μμF	Variable
C18	33μμF	±10 per cent
C19	1 μF	275 V
C20	5000 μμF	±1 per cent
C21	0·01 μF	350 V
C22	5000 μμF	±1 per cent
C23	0·001 μF	350 V
C24	8 μF	350 V
C25–C33	Not used	
C34	0·001 μF	
C35	0·001 μF	
C36	0·5 —5 μμF	Trimmer
C37	See page 22	
C38	0·5 —5 μμF	Trimmer
C39	1 μF	50 V
T1	Voltage Transformer Type R.T. 3.8	
T2	Current Transformer Type R.T. 4.8	
T3	Mains Transformer	
	Pri: 0–115 V+0–115 V Sec: 210–0–210 V, 40 mA 6·3 V, 1·75 A 6·3 V, 1·0 A	



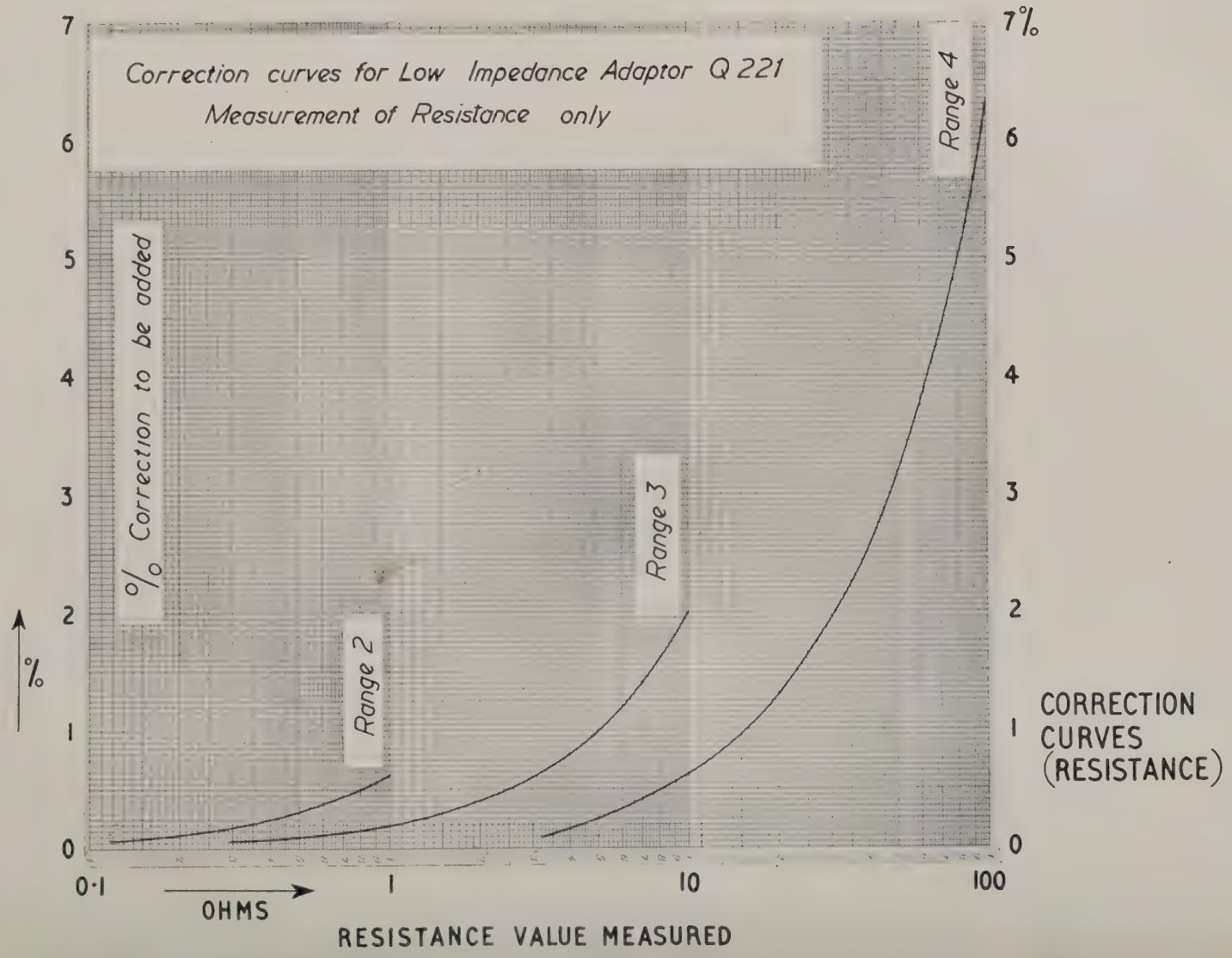
Ref.	Value	Type
R1	98·6 Ω	± 0·5 per cent
R2	314·8 Ω	± 0·5 per cent
R3	998·5 Ω	± 0·5 per cent
R4	3·161k Ω	± 0·5 per cent
R5	98·6 Ω	± 0·5 per cent
R6	314·8 Ω	± 0·5 per cent
R7	998·5 Ω	± 0·5 per cent
R8	3·161k Ω	± 0·5 per cent
C1	6000μμF	± 5 per cent
C2	450μμF	± 5 per cent
C3	68μμF	± 5 per cent
C4	10μμF	± 1μμF

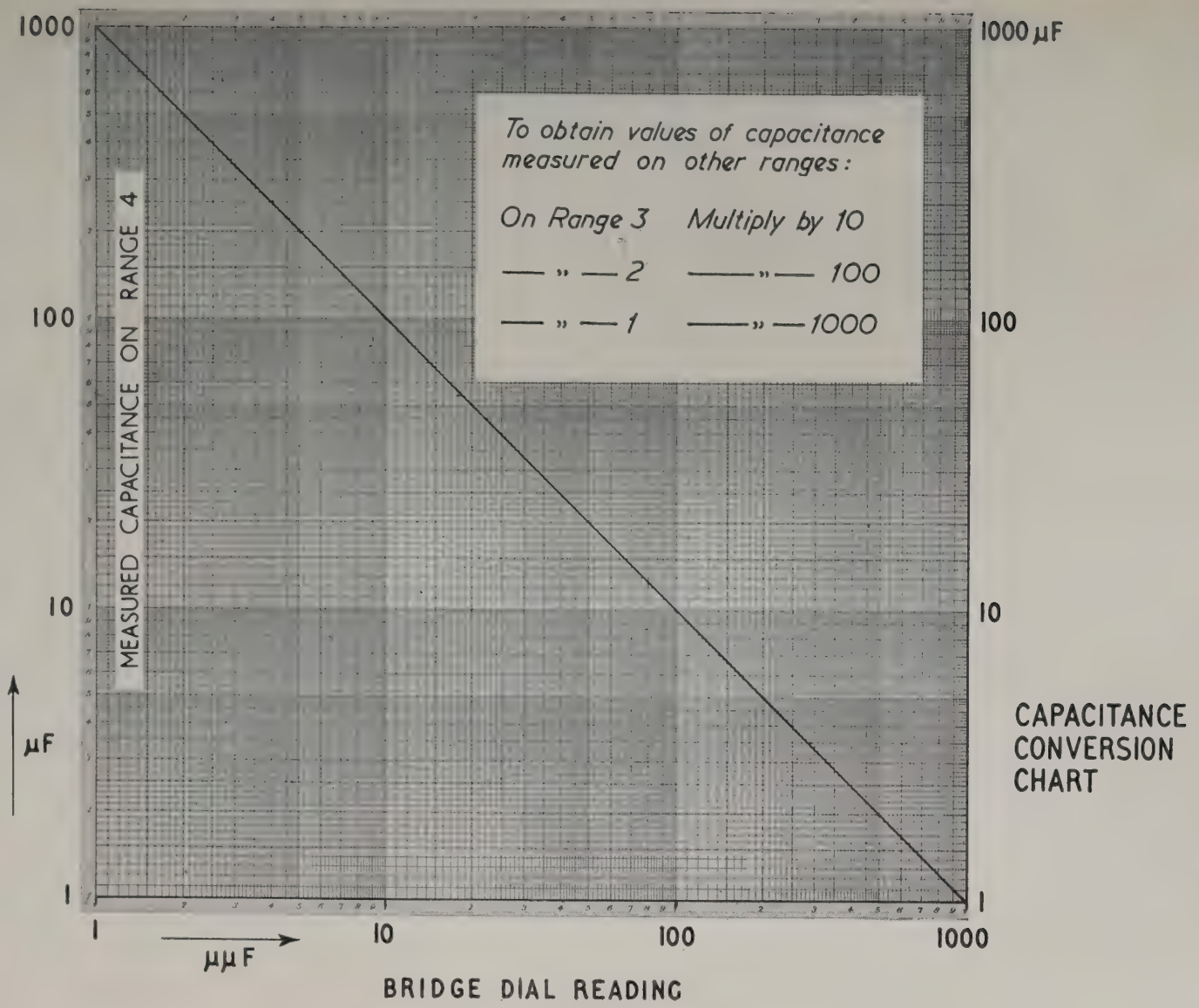


(Above) — B221
Circuit Diagram
(D3125, Issue L)

(Left) — Q221
Parts List and
Circuit Diagram
(D3378, Issue D)

Note : 6AM6 is equivalent to EF91.


Correction curves for Low Impedance Adaptor Q 221
Measurement of Resistance only
% Correction to be added
Range 2
Range 3
Range 4
%
7
6
5
4
3
2
1
0
0·1
1
10
100
OHMS
RESISTANCE VALUE MEASURED
CORRECTION CURVES (RESISTANCE)


1000
100
10
1
1000 µF
100
10
1
MEASURED CAPACITANCE ON RANGE 4
µF
To obtain values of capacitance measured on other ranges:
On Range 3 Multiply by 10
— " — 2 —— " — 100
— " — 1 —— " — 1000
CAPACITANCE CONVERSION CHART
1
10
100
1000
µµF
BRIDGE DIAL READING

	0	1	2	3	4	5	6	7	8	9
1·0	1·00000	99010	98039	97087	96154	95238	94340	93458	92593	91743
1·1	90909	90090	89286	88496	87719	86957	86207	85470	84746	84034
1·2	83333	82645	81967	81301	80645	80000	79365	78740	78125	77519
1·3	76923	76336	75758	75188	74627	74074	73529	72993	72464	71942
1·4	71429	70922	70423	69930	69444	68966	68493	68027	67568	67114
1·5	66667	66225	65789	65359	64935	64516	64103	63694	63291	62893
1·6	62500	62112	61728	61350	60976	60606	60241	59880	59524	59172
1·7	58824	58480	58140	57803	57471	57143	56818	56497	56180	55866
1·8	55556	55249	54945	54645	54348	54054	53763	53476	53191	52910
1·9	52632	52356	52083	51813	51546	51282	51020	50761	50505	50251
2·0	50000	49751	49505	49261	49020	48780	48544	48309	48077	47847
2·1	47619	47393	47170	46948	46729	46512	46296	46083	45872	45662
2·2	45455	45249	45045	44843	44643	44444	44248	44053	43860	43668
2·3	43478	43290	43103	42918	42735	42553	42373	42194	42017	41841
2·4	41667	41494	41322	41152	40984	40816	40650	40486	40323	40161
2·5	40000	39841	39683	39526	39370	39216	39063	38911	38760	38610
2·6	38462	38314	38168	38023	37879	37736	37594	37453	37313	37175
2·7	37037	36900	36765	36630	36496	36364	36232	36101	35971	35842
2·8	35714	35587	35461	35336	35211	35088	34965	34843	34722	34602
2·9	34483	34364	34247	34130	34014	33898	33784	33670	33557	33445
3·0	33333	33223	33113	33003	32895	32787	32680	32573	32468	32362
3·1	32258	32154	32051	31949	31847	31746	31646	31546	31447	31348
3·2	31250	31153	31056	30960	30864	30769	30675	30581	30488	30395
3·3	30303	30211	30120	30030	29940	29851	29762	29674	29586	29499
3·4	29412	29326	29240	29155	29070	28986	28902	28818	28736	28653
3·5	28571	28490	28409	28329	28249	28169	28090	28011	27933	27855
3·6	27778	27701	27624	27548	27473	27397	27322	27248	27174	27100
3·7	27027	26954	26882	26810	26738	26667	26596	26525	26455	26385
3·8	26316	26247	26178	26110	26042	25974	25907	25840	25773	25707
3·9	25641	25575	25510	25445	25381	25316	25253	25189	25126	25063
4·0	25000	24938	24876	24814	24752	24691	24631	24570	24510	24450
4·1	24390	24331	24272	24213	24155	24096	24038	23981	23923	23866
4·2	23810	23753	23697	23641	23585	23529	23474	23419	23364	23310
4·3	23256	23202	23148	23095	23041	22989	22936	22883	22831	22779
4·4	22727	22676	22624	22573	22523	22472	22422	22371	22321	22272
4·5	22222	22173	22124	22075	22026	21978	21930	21882	21834	21786
4·6	21739	21692	21645	21598	21552	21505	21459	21413	21368	21322
4·7	21277	21231	21186	21142	21097	21053	21008	20964	20921	20877
4·8	20833	20790	20747	20704	20661	20619	20576	20534	20492	20450
4·9	20408	20367	20325	20284	20243	20202	20161	20121	20080	20040
5·0	20000	19960	19920	19881	19841	19802	19763	19724	19685	19646
5·1	19608	19569	19531	19493	19455	19417	19380	19342	19305	19268
5·2	19231	19194	19157	19120	19084	19048	19011	18975	18939	18904
5·3	18868	18832	18797	18762	18727	18692	18657	18622	18587	18553
5·4	18519	18484	18450	18416	18382	18349	18315	18282	18248	18215
	0	1	2	3	4	5	6	7	8	9

PROPORTIONAL PARTS OF MEAN DIFFERENCES

	1	2	3	4	5	6	7	8	9
1·0									
1·1									
1·2									
1·3									
1·4									
1·5	42	83	125	167	209	250	292	334	375
1·6	37	74	110	147	184	221	258	294	331
1·7	33	65	98	131	164	196	229	262	294
1·8	29	58	88	117	146	175	204	234	263
1·9	26	53	79	105	132	158	184	210	237
2·0	24	48	71	95	119	143	167	190	214
2·1	22	43	65	86	108	130	151	173	194
2·2	20	40	59	79	99	119	139	158	178
2·3	18	36	54	72	91	109	127	145	163
2·4	17	33	50	67	84	100	117	134	150
2·5	15	31	46	62	77	92	108	123	139
2·6	14	29	43	57	72	86	100	114	129
2·7	13	26	40	53	66	79	92	106	119
2·8	12	25	37	49	62	74	86	98	111
2·9	12	23	35	46	58	69	81	92	104
3·0	11	22	32	43	54	65	76	86	97
3·1	10	20	30	40	51	61	71	81	91
3·2	10	19	29	38	48	57	67	76	86
3·3	9	18	27	36	45	53	62	71	80
3·4	8	17	25	34	42	50	59	67	76
3·5	8	16	24	32	40	47	55	63	71
3·6	8	15	23	30	38	45	53	60	68
3·7	7	14	21	28	36	43	50	57	64
3·8	7	14	20	27	34	41	48	54	61
3·9	6	13	19	26	32	38	45	51	58
4·0	6	12	18	24	31	37	43	49	55
4·1	6	12	17	23	29	35	41	46	52
4·2	6	11	17	22	28	33	39	44	50
4·3	5	11	16	21	27	32	37	42	48
4·4	5	10	15	20	26	31	36	41	46
4·5	5	10	14	19	24	29	34	38	43
4·6	5	9	14	18	23	28	32	37	41
4·7	4	9	13	18	22	26	31	35	40
4·8	4	9	13	17	22	26	30	34	39
4·9	4	8	12	16	20	25	29	33	37
5·0	4	8	12	16	20	24	27	31	35
5·1	4	8	11	15	19	23	26	30	34
5·2	4	7	11	15	18	22	25	29	33
5·3	3	7	10	14	18	21	24	28	31
5·4	3	7	10	14	17	20	24	27	30
	1	2	3	4	5	6	7	8	9

PROPORTIONAL PARTS OF MEAN DIFFERENCES

	0	1	2	3	4	5	6	7	8	9
5·5	18182	18149	18116	18083	18051	18018	17986	17953	17921	17889
5·6	17857	17825	17794	17762	17731	17699	17668	17637	17606	17575
5·7	17544	17513	17483	17452	17422	17391	17361	17331	17301	17271
5·8	17241	17212	17182	17153	17123	17094	17065	17036	17007	16978
5·9	16949	16920	16892	16863	16835	16807	16779	16750	16722	16694
6·0	16667	16639	16611	16584	16556	16529	16502	16474	16447	16420
6·1	16393	16367	16340	16313	16287	16260	16234	16207	16181	16155
6·2	16129	16103	16077	16051	16026	16000	15974	15949	15924	15898
6·3	15873	15848	15823	15798	15773	15748	15723	15699	15674	15649
6·4	15625	15601	15576	15552	15528	15504	15480	15456	15432	15408
6·5	15385	15361	15337	15314	15291	15267	15244	15221	15198	15175
6·6	15152	15129	15106	15083	15060	15038	15015	14993	14970	14948
6·7	14925	14903	14881	14859	14837	14815	14793	14771	14749	14728
6·8	14706	14684	14663	14641	14620	14599	14577	14556	14535	14514
6·9	14493	14472	14451	14430	14409	14388	14368	14347	14327	14306
7·0	14286	14265	14245	14225	14205	14184	14164	14144	14124	14104
7·1	14085	14065	14045	14025	14006	13986	13966	13947	13928	13908
7·2	13889	13870	13850	13831	13812	13793	13774	13755	13736	13717
7·3	13699	13680	13661	13643	13624	13605	13587	13569	13550	13532
7·4	13514	13495	13477	13459	13441	13423	13405	13387	13369	13351
7·5	13333	13316	13298	13280	13263	13245	13228	13210	13193	13175
7·6	13158	13141	13123	13106	13089	13072	13055	13038	13021	13004
7·7	12987	12970	12953	12937	12920	12903	12887	12870	12853	12837
7·8	12821	12804	12788	12771	12755	12739	12723	12706	12690	12674
7·9	12658	12642	12626	12610	12594	12579	12563	12547	12531	12516
8·0	12500	12484	12469	12453	12438	12422	12407	12392	12376	12361
8·1	12346	12330	12315	12300	12285	12270	12255	12240	12225	12210
8·2	12195	12180	12165	12151	12136	12121	12107	12092	12077	12063
8·3	12048	12034	12019	12005	11990	11976	11962	11947	11933	11919
8·4	11905	11891	11876	11862	11848	11834	11820	11806	11792	11779
8·5	11765	11751	11737	11723	11710	11696	11682	11669	11655	11641
8·6	11628	11614	11601	11587	11574	11561	11547	11534	11521	11507
8·7	11494	11481	11468	11455	11442	11429	11416	11403	11390	11377
8·8	11364	11351	11338	11325	11312	11299	11287	11274	11261	11249
8·9	11236	11223	11211	11198	11186	11173	11161	11148	11136	11123
9·0	11111	11099	11086	11074	11062	11050	11038	11025	11013	11001
9·1	10989	10977	10965	10953	10941	10929	10917	10905	10893	10881
9·2	10870	10858	10846	10834	10823	10811	10799	10787	10776	10764
9·3	10753	10741	10730	10718	10707	10695	10684	10672	10661	10650
9·4	10638	10627	10616	10604	10593	10582	10571	10560	10549	10537
9·5	10526	10515	10504	10493	10482	10471	10460	10449	10438	10428
9·6	10417	10406	10395	10384	10373	10363	10352	10341	10331	10320
9·7	10309	10299	10288	10277	10267	10256	10246	10235	10225	10215
9·8	10204	10194	10183	10173	10163	10152	10142	10132	10121	10111
9·9	10101	10091	10081	10070	10060	10050	10040	10030	10020	10010
	0	1	2	3	4	5	6	7	8	9

	1	2	3	4	5	6	7	8	9
5·5	3	7	10	13	16	20	23	26	29
5·6	3	6	9	13	16	19	22	25	28
5·7	3	6	9	12	15	18	21	24	27
5·8	3	6	9	12	15	18	20	23	26
5·9	3	6	9	11	14	17	20	23	25
6·0	3	6	8	11	14	16	19	22	25
6·1	3	5	8	11	13	16	19	21	24
6·2	3	5	8	10	13	15	18	21	23
6·3	2	5	7	10	12	15	17	20	22
6·4	2	5	7	10	12	14	17	19	22
6·5	2	5	7	9	12	14	16	19	21
6·6	2	5	7	9	11	14	16	18	20
6·7	2	4	7	9	11	13	15	18	20
6·8	2	4	6	9	11	13	15	17	19
6·9	2	4	6	8	10	12	14	17	19
7·0	2	4	6	8	10	12	14	16	18
7·1	2	4	6	8	10	12	14	16	18
7·2	2	4	6	8	10	11	13	15	17
7·3	2	4	6	7	9	11	13	15	17
7·4	2	4	5	7	9	11	13	15	16
7·5	2	4	5	7	9	11	12	14	16
7·6	2	3	5	7	9	10	12	14	15
7·7	2	3	5	7	8	10	12	13	15
7·8	2	3	5	7	8	10	11	13	15
7·9	2	3	5	6	8	9	11	13	14
8·0	2	3	5	6	8	9	11	12	14
8·1	2	3	5	6	8	9	11	12	14
8·2	1	3	4	6	7	9	10	12	13
8·3	1	3	4	6	7	9	10	11	13
8·4	1	3	4	6	7	8	10	11	13
8·5	1	3	4	5	7	8	10	11	12
8·6	1	3	4	5	7	8	9	11	12
8·7	1	3	4	5	7	8	9	10	12
8·8	1	3	4	5	6	8	9	10	12
8·9	1	3	4	5	6	8	9	10	11
9·0	1	2	4	5	6	7	9	10	11
9·1	1	2	4	5	6	7	8	10	11
9·2	1	2	4	5	6	7	8	9	11
9·3	1	2	4	5	6	7	8	9	10
9·4	1	2	3	4	6	7	8	9	10
9·5	1	2	3	4	5	7	8	9	10
9·6	1	2	3	4	5	6	8	9	10
9·7	1	2	3	4	5	6	7	8	10
9·8	1	2	3	4	5	6	7	8	9
9·9	1	2	3	4	5	6	7	8	9
	1	2	3	4	5	6	7	8	9

$\frac{1}{100C}$

$C_M F$

$L H.$

$\frac{1}{.0052}$

$\frac{100}{52}$

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